THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

District heating in future Europe: Modelling expansion potentials and mapping heat synergy regions

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Gothenburg, Sweden 2015

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ISBN 978-91-7597-088-2

Doktorsavhandlingar vid Chalmers tekniska högskola

Ny serie nr 3769

ISSN 0346-718X

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Telephone +46 (0) 31 772 10 00

Printed by Chalmers Reproservice

Göteborg, Sweden 2015

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Abstract

This thesis presents a set of methodologies and approaches to investigate and determine the extent by which district heating can contribute to improved energy system efficiency and reduced carbon dioxide emissions in future Europe. The main motivation for suggesting large-scale implementation of district heating as a structural energy efficiency measure to obtain these objectives originates essentially in the predicament that a majority of European buildings today remain highly dependent on fossil fuels to provide energy needed for space heating and hot water preparation. In parallel, vast annual volumes of rejected excess heat from European power plants and industries are mainly neglected and lost unutilised to the ambient surroundings, why extended recovery and utilisation of such secondary energy assets realistically could replace significant shares of current inefficient supplies by fuel substitution. A prerequisite, however, for the viability of this logical prospect, is that infrastructures by which to facilitate excess heat recovery and subsequent network heat distribution are in place, which by no means is the average case in contemporary Europe.

Hereby, the investigation is structured orderly by first establishing whether district heating can be a competitive alternative on current urban European heat markets, facilitated by a distribution capital cost model, where after the energy systemic benefits of expanding district heating are characterised and used to estimate a plausible expansion potential based on comparative analysis. Next, energy system modelling of continental EU27 by the year 2050, with district heating expanded in alignment with this potential, is performed to assess the total energy system cost benefits relative an alternative scenario focusing mainly on individual energy efficiency measures. Finally, spatial mapping to identify current primary target regions from which large-scale implementation of district heating could emanate is conceived and performed by use of a geographical information systems interface.

The findings are generally supportive of a realisation of the objectives, mainly so by establishing a three-fold directly feasible expansion potential for district heating in city areas, but recognise also several additional, mainly non-technical, issues and challenges necessary to address in a successful transition to more energy efficient supply structures in future Europe.

Keywords: district heating, energy efficiency, distribution capital cost, heat demand density, plot ratio, excess heat recovery, sequential energy supply, heat utilisation rate, effective width

List of publications

This thesis is based on the following appended papers.

I. Heat distribution and the future competitiveness of district heating
Persson U., Werner S.
Applied Energy (2011), 88: 568-576

II. Effective width - the relative demand for district heating pipe lengths in city areas
Persson U., Werner S.
12th International Symposium on District Heating and Cooling. Tallinn, Estonia. September 5-7 (2010): 128-131

III. District heating in sequential energy supply
Persson U., Werner S.
Applied Energy (2012), 95: 123–131

IV. Heat Roadmap Europe: Combining district heating with heat savings to decarbonise the EU energy system
Connolly D., Lund H., Vad Mathiesen B., Werner S., Möller B., Persson U., Boermans T., Trier D., Alberg Östergaard P., Nielsen S.
Energy Policy (2014), 65: 475–489

V. On the use of surplus electricity in district heating systems
Averfalk H., Ingvarsson P., Persson U., Werner S.
14th International Symposium on District Heating and Cooling. Stockholm, Sweden. September 8-9 (2014)

VI. Heat Roadmap Europe: Identifying strategic heat synergy regions
Persson U., Möller B., Werner S.
Energy Policy (2014), 74: 663–681.

Urban Persson has been the main author of Papers I, II, III and VI, and co-author on Papers IV and V. In Paper IV, Urban Persson contributed mainly in spatial analyses for the pan-European heat atlas and in assessments of local excess and renewable heat resource potentials. The energy system modelling was performed by David Connolly at Aalborg University, Denmark. In Paper V, Urban Persson participated mainly in manuscript writing and data analysis. Professor Sven Werner has been main supervisor for all papers and have contributed in the development of theory (Papers I, II, V and VI), in data analyses (Papers I, II, III, IV and V), and in discussions (Papers I, III, V and VI). Sven Werner has further provided ideas and support in the work of all papers, as well as in submission and revision processes. Urban Persson has also participated in additional papers and reports during his doctoral studies. The following publications, which have in common that they all constitute preparatory or parallel work in relation to the appended papers, are not included in this thesis:

- Competitiveness of European district heating systems
  Persson U., Werner S.
  Chapter 33 in: European Energy Pathways - Pathways to Sustainable European Energy Systems (2011): 283-290.
  Alliance for Global Sustainability (AGS). ISBN 987-91-978585-1-9

- Evaluating competitiveness of district heating using a distribution capital cost model
  Persson U., Werner S.
  Chapter 25 in: Methods and Models - Pathways to Sustainable European Energy Systems (2011): 157-160.
  Alliance for Global Sustainability (AGS). ISBN 987-91-978585-2-6

- Heat Roadmap Europe - First pre-study for EU27
  Connolly D., Lund H., Vad Mathiesen B., Werner S., Möller B., Persson U., Nilsson D., Trier D., Alberg Östergaard P., Nielsen S.
  Euroheat & Power (2012). Brussels, Belgium

- Mapping local European heat resources – a spatial approach to identify favourable synergy regions for district heating
  Persson U., Nilsson D., Möller B., Werner S.
  13th International Symposium on District Heating and Cooling. Copenhagen, Denmark. September 3-4 (2012): 260-269

- Heat Roadmap Europe - Second pre-study for EU27
  Connolly D., Lund H., Vad Mathiesen B., Werner S., Möller B., Persson U., Boermans T., Trier D., Alberg Östergaard P., Nielsen S.
  Euroheat & Power (2013). Brussels, Belgium

- The role of district heating in decarbonising the EU energy system and a comparison with existing strategies
  Connolly D., Lund H., Vad Mathiesen B., Werner S., Möller B., Persson U., Trier D., Alberg Östergaard P., Nielsen S.
  8th Conference on Sustainable Development of Energy, Water and Environment Systems. Dubrovnik, Croatia. September 22-27 (2013)

- Towards fourth generation district heating – Experiences with and potential of low temperature district heating.
  Dalla Rosa A., Li H., Svendsen S., Werner S., Persson U., Ruehling K., Felsmann C., Crane M., Burzynski R., Bevilacqua C.
  International Energy Agency (IEA). Implementing Agreement, DHC/CHP Annex X. Final report, September (2014).

Contents

Notations

a	Annuity	1/a
α	Specific building space	m^2/n
A_B	Total building space area	m^2
A_L	Total land area	m^2
C_d	Distribution capital cost	€/GJ
C_1	Construction cost constant	€/m
C_2	Construction cost coefficient	€/m^2
d_a	Average pipe diameter	m
e	Plot ratio	-
E_{abs}	Absorbed energy	J
E_{excess}	Excess heat	J
E_{heat}	Recovered excess heat	J
$E_{heat,o}$	Recoverable excess heat (theoretical)	J/a
E_{prim}	Primary energy supply	J
$E_{prim,a}$	Primary energy supply to any given activity	J/a
η_{abs}	Absorption efficiency	%
η_{heat}	Recovery efficiency	%
η_{tot}	Total conversion efficiency	%
f_{CO2}	Carbon dioxide emission factor	g,CO_2/MJ
I	Total network investment cost	€
L	Total trench length	m
$m_{CO2,a}$	Carbon dioxide emissions from any given activity	kg/a
n	Investment lifetime	a
P	Total population	n
p	Population density	n/km^2
q	Specific heat demand (1)	GJ/m^2,a

q	Specific heat demand (2)	GJ/n
q_L	Heat demand density	GJ/m^2
Q_S	Heat annually sold	J/a
Q_S/L	Linear heat density	GJ/m
Q_{tot}	Total heat demand	J
r	Interest rate	%
sf_{CO2}	Standard carbon dioxide emission factor	g,CO$_2$/MJ
w	Effective width	m
ξ_{heat}	Heat utilisation rate	%
$\xi_{heat,o}$	Excess heat ratio	%
ζ_{heat}	Heat recovery rate	%

Nomenclature

Absorbed energy	Energy absorbed in the primary product of energy transformations. In thermal power generation equal to generated electricity. In industrial processes equal to energy added or maintained in industrial products
Absorption efficiency	Share of absorbed energy from total primary energy supply (in thermal power generation equal to electrical efficiency)
ArcMap	Geographical Information Systems (GIS) desktop software, from Environmental Systems Research Institute (ESRI)
Autoproducer	Enterprise that produces electricity and/or heat for own use in support of its main business, but not as main business
Central conversion	Fuel transformations of primary energy supply to secondary energy commodities in energy sector
Cogeneration	Simultaneous generation of electricity and heat (also combined heat and power, CHP)
Conversion efficiency	Share of useful energy derived from a primary or secondary energy input (may refer to total systems, sub-systems, and/or single components)
End use	Usable energy demand of energy commodities available in consumer sectors (corresponding to net customer heat and power demands)
Energy balance	Quantified and/or relational description of energy flow volumes at three principal supply/demand strata in an energy system: primary energy supply (level 1), final consumption (level 2), and end use (level 3)
Energy commodity	Fuel, heat and/or electricity (also energy carrier)
EnergyPLAN	Energy systems analysis tool specifically designated to assist in the design of national and/or regional energy planning strategies
Energy savings	Behavioural measure reducing primary energy demands by absolute decreases of end use energy demands
Excess heat	All rejected heat in thermal power generation not absorbed as electricity. All rejected heat in industrial processes not added or maintained in industrial products conceived available for recovery (also surplus heat or waste heat)
Excess heat ratio	Quota of recoverable excess heat volumes relative to total building heat demands at regional level

Final consumption	Energy commodities available in consumer sectors for end use (corresponding to gross customer heat and power demands)
Fossil fuels	Natural resources formed from biomass in the geological past
Fuel	Any substance burned as a source of heat or power
Fuel transformation	Conversion of a primary fuel, by physical and/or chemical means, into a secondary energy commodity (also energy transformation)
Gross domestic product	Market value of final goods and services produced in a country/region during a given time period
Heat demand	End use energy demands for low temperature heating purposes in buildings
Heat demand density	Sum of total or sector heat demands in a given land area, by the land area
Heat recovery rate	Share of recovered excess heat from total excess heat
Heat utilisation rate	Share of recovered excess heat of total heat demand
Individual energy efficiency measure	Technical/systemic measure reducing primary energy demands by absolute decreases of end use energy demands and/or by increased conversion efficiencies in central or local conversion while reducing equivalent end use levels
Linear heat density	Annually sold heat in a district heating system by the total length of the pipe network
Local conversion	Fuel transformations and conversions of primary and/or secondary energy commodities in final consumption
Main activity	Enterprise that produces electricity and/or heat as main business (also public and/or main producer)
NUTS3 region	Third level of European administrative units
Plot ratio	Fraction of total building space area in a given land area (also product of population density and specific building space)
Population density	Total population in a given land area, by the land area
Power producer	Enterprise generating electricity only (also power-only producer)

Primary electricity	Electricity generation obtained from natural sources (hydro-, wind-, solar-, tide-, and wave power)
Primary energy supply	Energy commodities extracted or captured directly from natural resources (also primary energy commodities)
Primary heat	Heat obtained from natural sources such as geothermal and solar thermal power
Recovered excess heat	Excess heat recovered for utilisation as usable heat in buildings, industries, and energy sector facilities
Recovery efficiency	Share of recovered excess heat from total primary or secondary energy supply
Renewable energy	Energy commodities drawn directly or indirectly from current or recent flows of the constantly available solar and gravitational energy
Secondary electricity	Electricity generated from the heat of nuclear fission, from geothermal and solar thermal heat, and by burning of combustible primary fuels (thermal power generation)
Secondary energy commodities	All energy commodities which are not primary but generated from primary energy commodities
Secondary heat	Heat obtained from the nuclear fission of nuclear fuels, and by burning combustible primary fuels. Heat generated by transforming electricity to heat in electric boilers or heat pumps (also excess heat)
Strategic heat synergy region	A single NUTS3 region, or a cluster of neighbouring NUTS3 regions, that within its boundaries contain large and concentrated heat demand centres as well as significant excess heat resources located in near vicinity of each other
Structural energy efficiency measure	Technical/systemic measure reducing primary energy demands by increased recovery efficiencies in central or local conversion while maintaining equivalent end use levels
Thermal power generation	Heat and power generation in energy and industry sectors by means of fuel transformations and various applications of the dual vapour-liquid Rankine cycle
Waste-to-Energy (WTE)	Energy recovery from non-recoverable or non-compostable fractions of municipal and/or industrial waste by incineration

to my family…

“The world is my representation”

Arthur Schopenhauer

1 Introduction

The awareness of climate change and the threat to our planet's thermal balance that has arisen from human activities during the industrial era is common knowledge today. Throughout the rise and maturation of electrification, urbanisation, and global transport, however, this insight remained predominantly dormant and was not to emerge with collective emphasis until the clash of the energy crises in the 1970s. Climatologists, which already in the 1960s had observed and correlated steadily increasing global temperatures with increasing levels of carbon dioxide in the atmosphere, had found support for this assertion from incipient ice core research as well as from other scientific fields, from farmers, fishermen, and amateur nature observers (UNFCCC, 2014a). Let aside this and alarming early modelling projections raising the issue of interdependency between economic growth, population developments and resource depletion (Meadows et al., 1972)[1], a first comprehensive and multilateral statement revealing a wider adoption of this understanding came with the United Nations World Commission on Environment and Development report "Our Common Future" (WCED, 1987), also known as the Brundtland report[2]. Forwarding the concept of sustainability herein, and further stressing a holistic perspective including social, economic, environmental, and energy system dimensions in the realisation of this idea, the message of concern was one reluctantly received and reconciled by a rapidly growing community of world citizens.

In 1992, at the United Nations Conference on Environment and Development in Rio de Janeiro (the first Earth Summit), negotiations produced a pioneering international treaty to stabilise greenhouse gas concentrations in the atmosphere. This treaty, the United Nations Framework Convention on Climate Change (UNFCCC, 1992), although legally non-binding, was originally signed by 154 nations and later ratified by more than 190 nations (UNFCCC, 2014b). One of several agreements shared by the Parties of the Convention was the recognition that:

> *"… steps required to understand and address climate change will be environmentally, socially, and economically most effective if they are based on relevant scientific, technical, and economic considerations and continually re-evaluated in the light of new findings in these areas"* (p. 2)

Just prior to the Energy Summit, the International Panel on Climate Change (IPCC), a scientific intergovernmental body established in 1988 under the auspices of the United Nations (and later awarded the Nobel Peace Prize (2007)), had published its first of five comprehensive assessment reports in support of the Framework Convention. In the first assessment, which recognised the presence of a natural global greenhouse effect, it was confirmed with certainty that emissions resulting from human activities "substantially increases the concentration of greenhouse gases in the atmosphere", which enhances the greenhouse effect and consequently results in additional warming of the Earth's surface

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[1] The so-called Club of Rome, still committed today to identify crucial problems for the future of humanity through analysis and research, followed up their first projections in a series of subsequent model runs (Club of Rome, 2014).

[2] In the early 1970s, environmental concerns had received general attention at e.g. the United Nations Conference on the Human Environment in Stockholm 1972 (UNEP, 2014b). Also more specific issues, such as the depletion of the ozone layer, was later addressed in the 1985 Vienna Convention for the Protection of the Ozone Layer (UNEP, 2014c), with the subsequent associated 1987 Montreal Protocol (UNEP, 2014a).

(IPCC, 1990). Although disputed[3], this statement was to assert a core influence on the general discourse of national and international environmental and energy policy in the following decades. As the uncomfortable idea – that we ourselves and our energy dependent activities are endangering our own living space – gradually was assimilated, traditional perceptions of energy systems structures and common conversion technologies (as conceived during most of the fossil era) became increasingly questioned and eventually challenged by new concepts such as e.g. energy savings, energy efficiency, and renewable energy systems (Connolly and Mathiesen, 2014; Ecofys, 2011; Eurelectric, 2010; Lund, 2014; Lund and Mathiesen, 2009; Lund et al., 2010).

Given the complexity of the climate change issue, i.e. the stealth interdependencies between economic and population growth, between energy use and resource depletion, between local emissions and a global atmosphere, between justice and inequity, wealth and poverty etc., it is fair to assume that no single action will accomplish the greenhouse gas emission reductions needed not to exceed targeted levels (UN, 1998). If, at all, humankind is to resolve this infernal challenge in due time and manage to steer civilisation towards a path of sustainable resource utilisation, it will be only by the intelligent coordination and application of a wide variety of measures, technologies, and system solutions. The prompt deployment of concrete, realistic, effective, and feasible solutions to alter current trends seem to be the only remaining option. Statistics show, in spite of international treaties of common understanding, agreements on emission targets, and the sober message from an unambiguous community of leading world scientists that these trends continue to represent a literal up-hill endeavour for humanity to climb, as outlined in Fig. 1. In terms of annual carbon dioxide emissions from energy related activities, there are some positive indications that North American and European total emission volumes have stabilised and even started to decrease during recent years, but for all other world regions, and for the World as such, the propagation is alarming and all but satisfactory.

By what steps, then… we should ask ourselves, are we to understand and address climate change from here on, and forward? What measures, technologies, and system solutions may realistically lead to reduced primary energy supplies as the demand for energy services facilitated by these supplies continue to increase? Well, from an energy systems perspective, at least, three main conceptual pathways to decarbonise human, yet fossil-based, energy related activities appear to be passable[4]. Corresponding to the three main energy system strata of end use, final consumption, and primary energy supply, constituents of any energy balance, these paths all result in reduced primary energy demands – but with different consequences on the availability of end use energy. First, energy savings, mainly in end use, reduces primary energy demands simply by avoiding the use of given energy services. Behavioural, as such, this measure has no cost but imposes limits on public activity and industrial production. Second, individual energy efficiency measures, which represent e.g. improved thermal properties of buildings and increased conversion efficiencies of technical equipment in final consumption and end use, reduce primary energy demands but are associated to investment, operation, and maintenance costs. Third, structural energy efficiency measures, which by improved recovery efficiencies of central and local conversion processes reduce primary

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[3] The scientific and public debate under following decades whether to confute or confirm such an anthropogenic interference, partly fuelled by the IPCC incapacity to present 100% evidence, can be interpreted as a sign that the scientific process and community is healthy and applies a critical approach to any postulates. The debate, however, is beyond the scope of this thesis and not explored further in this context.

[4] There is of course a fourth pathway; a 100% renewable energy system. Eventually, but still vaguely distant, solar, wind, biomass, geothermal, and other self-replenishing energy sources should constitute the natural basis of profound sustainable energy systems in the future.

energy demands and increase total energy system efficiency, are as well associated to investment, operation, and maintenance costs, but inflict no reduction of end use levels.

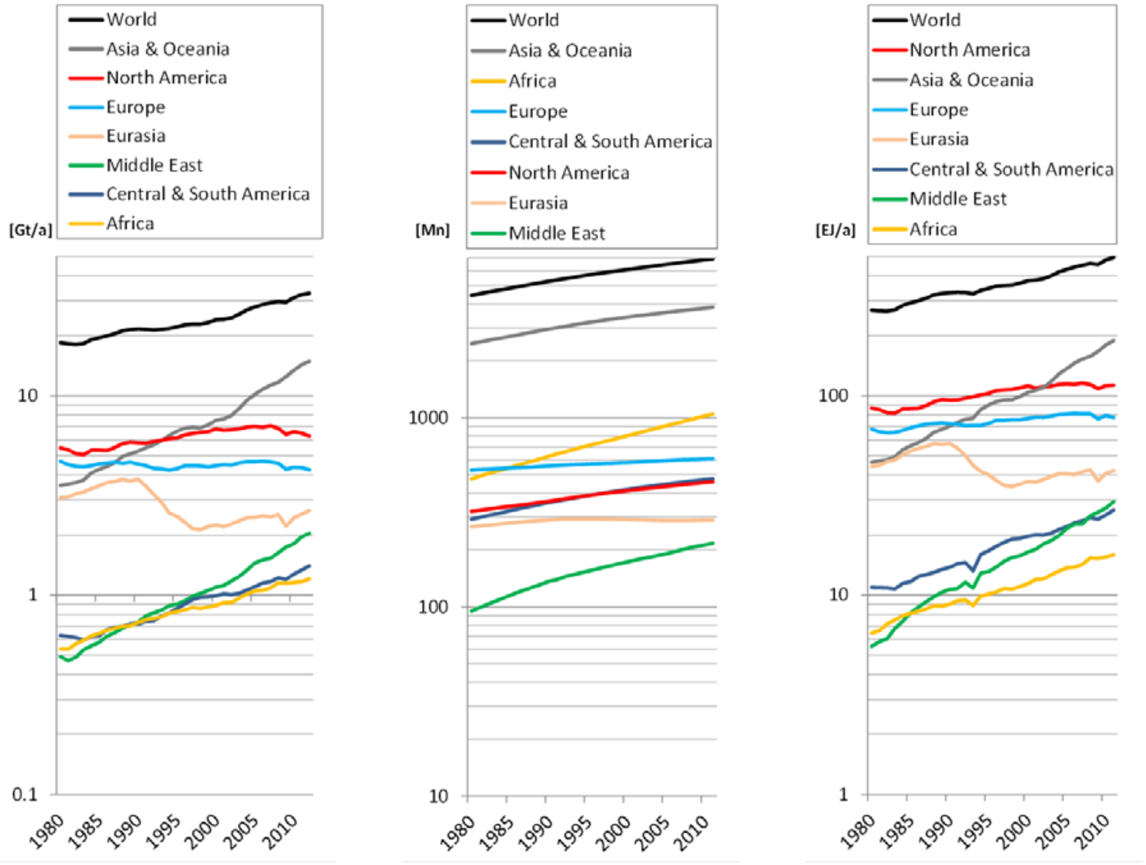

Fig. 1. World and world regions developmental trends from 1980 to 2012 for total annual carbon dioxide emissions from energy consumption (left), total population counts (centre), and total primary energy supply (right). Source: (EIA, 2014b).

The technological and organisational concepts studied in this thesis, i.e. district heating and heat recovery, belong to the latter of these three principal steps. As district heating systems and network heat distribution emerged in the late 19th century (Collins, 1959; Margolis, 1927; Pierce, 1993; Raynal et al., 1992; Werner, 1989), this also marked the introduction of a principal concept with the capacity to improve central conversion efficiencies of energy and industry sector activities, and which, if fossil-based, in turn reduces greenhouse gas emissions on local, regional, and global scales (Frederiksen and Werner, 2013; IEA, 1983, 2009). Consequently, district heating is recognised here as an energy efficient and environmentally advantageous solution for the heating of buildings, since delivered and utilised heat should originate in recovered excess heat from already converted primary energy sources – rejected secondary heat that would otherwise be wasted (Holmgren, 2006; IEA, 2008; Persson and Werner, 2012; Werner, 2004). As will be presented further in this thesis, especially so in appended Paper III, such central and local conversion heat losses remain substantial in Europe as well as in other world regions today, and unfortunately; they contribute to total greenhouse gas emissions while not at all providing any useful energy services. Increased recovery of rejected excess heat from fuel transformations in energy and industry sectors, as well as from other industrial processes and local renewable heat resources, which in essence is conceivable only if the appropriate means for heat distribution are present, thus represents one optional pathway towards a more sustainable future for Europe and the industrialised world.

In relation to this thesis - which focuses on European conditions and which had been more or less impossible to conceive without the availability of public data – another offspring from the first Earth Summit, the so-called “Rio Convention” (UN, 1992), is of key importance. As stated in the tenth Principle of the first Annex herein: “At the national level, each individual shall have appropriate access to information concerning the environment that is held by public authorities”, and “States shall facilitate and encourage public awareness and participation by making information widely available”, the clear aim of the Convention signatories was to make environmental data transparent. In 1998, the Aarhus Convention (UNECE, 1998), a direct response to the ambitions of the Rio Convention and legally binding for ratifying Parties, drew up the general outline of what was later to become known as “Pollutant Release and Transfer Registers” (PRTRs)[5], i.e. coherent, integrated, and nationwide public data registers on facility emissions to land, water, and air. In the subsequent 2003 Kiev Protocol (UNECE, 2003), the general objectives to enhance such public access to information through the establishment of PRTRs were specified in detail and the Protocol is signed today by some 40 countries including the European Union (UN, 2014).

Publicly open data, environmental as well as demographical, geographical, and economic, has proven much useful in this work. Although initially perhaps not intended for energy systems analysis, open data parameters in combination with e.g. international energy statistics, has allowed several assessments to be performed that would otherwise most likely have been out-of-reach. One example of this is the central methodological step to identify strategic heat synergy regions in appended Paper VI, which involves estimates of annual excess heat volumes from energy and industry sector facilities based on a reversed calculation sequence and (public) carbon dioxide emission data. Another example is the concept of heat demand density introduced in appended Paper IV, where (open) geographical data in combination with energy statistics on building sector energy use allow spatial determination of heat demand distributions. A third example is the distribution capital cost model for district heating systems presented in appended Papers I and II, a model investigation facilitated inter alia by the (open) Urban Audit database on European cities and city districts (ES, 2009a, b). Hence, a general contribution of this work lies in the idea to create new theoretical concepts by which to link non-energy related data parameters to energy-specific statistical parameters, which eventually widens the assessment horizon and expands the realm of energy systems analysis.

1.1 Research challenges

In 2010, the European Union was inhabited by some 503 million citizens (ES, 2014c), of which approximately 370 million lived in towns, cities, and large urban areas (UN, 2010). As detailed in Fig. 2 at left, total European population counts, primary energy supplies, and carbon dioxide emissions, show rather stable trends from 1990 to 2012 compared to corresponding world totals, and total primary energy supplies hover at some 70 EJ annually. To meet European Union energy efficiency targets set for 2020 however[6], a clear and steep decline during the coming years is conditional. If to honour the 2020 energy efficiency target,

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[5] See Article IV, Access to Environmental Information, and Article V, Collection and Dissemination of Environmental Information.

[6] European primary energy reductions expected from energy efficiency measures, originally referring to the Primes 2005 baseline scenario for EU25, according to (EC, 2005), are not in line with the originally conceived potential of 20% by 2020, as formalised in (EC, 2006). In a review of the Energy Efficiency plan 2011 (EC, 2011b), where the progress was evaluated by comparing the Primes 2007 baseline scenario and the 2009 energy efficiency scenario, it was concluded that the European Union will achieve only 8.9% (164 Mtoe ≈ 6.9 EJ) of the 20% efficiency objective (368 Mtoe ≈ 15.4 EJ). Currently, a new energy efficiency target considering a 30% reduction by the year 2030 is under discussion but have not yet been approved nor formalised.

EU28 (including Croatia as the 28th Member State since July 1st, 2013) will have to reduce total primary energy supplies to 62.1 EJ (EU, 2010a, 2013), which implies an annual decrease from current levels of approximately three percent annually (or some 2 EJ per year). A breakdown of the European primary energy supply, as presented in Fig. 2 at centre, reveals that efforts to achieve these reductions may target different end use categories, e.g. transport, electricity, and heat, but should – from the perspective held in this thesis – significantly so focus on improved energy system efficiency. Heat losses in central conversion processes constitute no less than 30% (22 EJ) of total primary energy supplies and corresponding heat losses in local conversion processes constitute another 24% (17 EJ), resulting in a total energy system efficiency of only 46% (i.e. 33 EJ correspond to the useful end use energy demand).

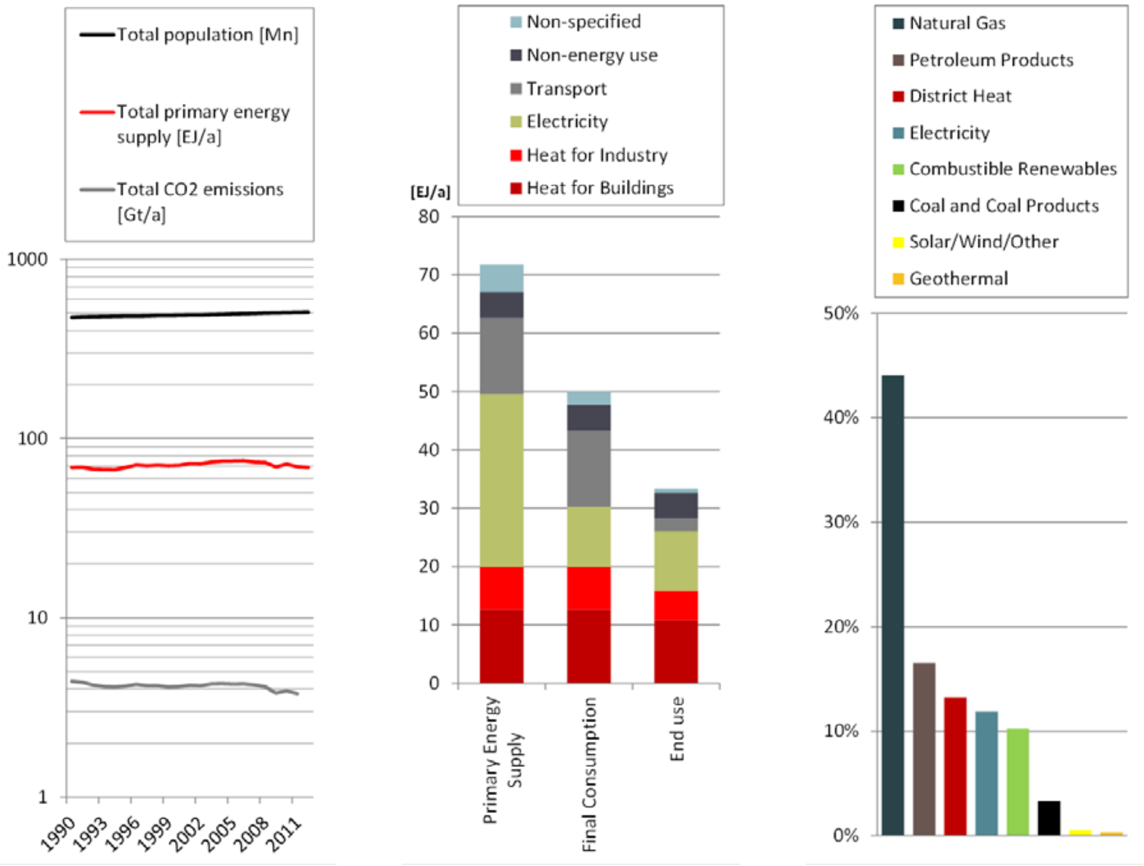

Fig. 2. EU27 developmental trends from 1990 to 2012 for total population, total primary energy supply, and total CO_2 emissions (left, including Croatia). Breakdown of the EU27 energy balance for 2010, by stratum and main user categories (centre). At right, detail of the EU27 heat market for 2010, by origin of heat supply for heat demands in residential and service sector buildings. Sources: (Bertoldi et al., 2012; EEA, 2013c; ES, 2014c; IEA, 2012a, 2014).

Buildings in the European Union account for 40% of final consumption energy demands (EC, 2013), and the end use energy volume for space heating and domestic hot water preparation in these buildings amounted to approximately 11.8 EJ in 2010 (not including industrial buildings or processes), see Fig. 2 at centre. When concentrating on buildings in residential and service sectors, for which the origin of heat supplies to meet prevailing heat demands are illustrated in Fig. 2 at right, the prolonged high dependency on individual – fossil-based – heat alternatives such as local boilers and electric resistance heaters is evident[7]. Due to this continued circumstance, continued in the sense that Europe in general has seen little changes in altering

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[7] Natural gas (44.1%), petroleum products (16.5%), district heat (13.2%), electricity (11.9%), combustible renewables (10.2%), coal and coal products (3.3%), solar/wind/other (0.5%), geothermal (0.3%).

this fossil dominance in the past, the residential and service sector heat market represent a key area to address in the decarbonisation of the European energy system. However, a central research challenge of this work lies in the fact that improved energy efficiency in the European building sector (with corresponding reduced carbon dioxide emissions from the provision of low temperature energy services to these buildings), can – in view of the three conceptual pathways – be obtained by principally different approaches.

One such approach is building renovations, which by e.g. improved insulation capacities of building envelope materials and deployment of new building techniques and standards, represents technical energy efficiency measures in final consumption whereby end use energy demands are lowered, thus requiring less energy supply to provide equivalent energy services. According to the Renovate Europe Campaign, an initiative of the European Alliance of Companies for Energy Efficiency in Buildings (EuroACE), the current renovation rate of the European building stock is 1.2% annually. The campaign suggests increased renovation rates (3.0% per year) before 2020 to reach its ambitions of an 80% reduction of total building energy demands by 2050 (REC, 2014). Given long average technical and service lifetimes of European buildings, and significant shares of historical buildings in many European cities, this ambition may prove hard to fulfil[8]. Another approach, highly efficient conversion technologies in final consumption, as e.g. individual compressor heat pumps, offer rich opportunities for substantial reductions of demands for energy supply while providing equivalent energy services, since ambient low temperature heat sources can be three-, four-, or even five-folded by the additional marginal supply of electricity[9]. In Germany, Sweden, France, and Austria especially (Robur, 2014), the installation rate of individual heat pumps have seen great increases in recent years and from a user perspective, reduced operational costs for heating makes this an attractive investment.

As such, both building renovations and efficient local conversion technologies should provide substantial end use energy demand reductions in the coming years; the question however, is to what extent the cost-effectiveness of these measures will persist in competition with the synergetic and resource-efficient benefits obtainable by extended use of district heating. Despite it being the sole representative of all central supply options for the heating of buildings that applies the principle of heat recycling, district heating is nonetheless associated with some general restrictions and conditions that need to be recognised. First, as in the case with any network distribution, the economy of network heat distribution is dependent on high transmission loads for feasibility (in the case of district heating systems this translates into high linear heat densities). Put shortly, the feasibility of district heat distribution is directly proportional to the population density of the target area at hand, which means that large cities and urban areas in general provide most beneficial economic conditions for network heat distribution. Second, quite contrary to gas and electricity networks, which extend beyond national borders and interconnect on continental scales, heat distribution infrastructures are strictly local. In this respect, network heat distribution is limited with respect to transmission distance and, despite examples of system merges in clustered large urban zones to form regional networks (Karlsson et al., 2009; Öresundskraft, 2014), have to be located in spatial cohesion with heat supply sources as well as with heat demand centres.

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[8] Buildings, their usage and condition, are a complex matter in itself. Over the real lifetime of a building, its use, structure, and design may go through several changes. Refurbishments and renovations are also subject for costs which, given the nature of ownership, geographical location, extent etc., may be troublesome to allocate. Nonetheless, renovations to improve thermal properties of buildings should be an essential part of the solution to decarbonise the European heat market.

[9] If equipped also with heat recovery from exhaust air, the efficiency of heat pumps may be further improved.

Third, district heating, sometimes dismissed as a commercially non-applicable practise given its partial association with former planned or mixed economies, represents expensive infrastructure investments that yet need to be competitive on narrow-margin heat markets. Given the current dominance of gas and electricity infrastructures on many such national EU28 Member State heat markets, what incentives are there to motivate heat sector actors to undertake the necessary investments in local heat infrastructures if the return on these investments are perhaps both uncertain and limited? In the Nordic (and Baltic) Member States, where district heating reaches highest national heat market shares among European Union Member States today, see Fig. 3 at left, dedicated municipal heat planning (DK (Chittum and Østergaard, 2014)) and taxation of fossil fuels for heating purposes (DK and SE (Di Lucia and Ericsson, 2014; Karlsson and Gustavsson, 2003; Reidhav and Werner, 2008)), have proven effective policy measures to provide incitements for large-scale deployment and decarbonisation of district heating systems.

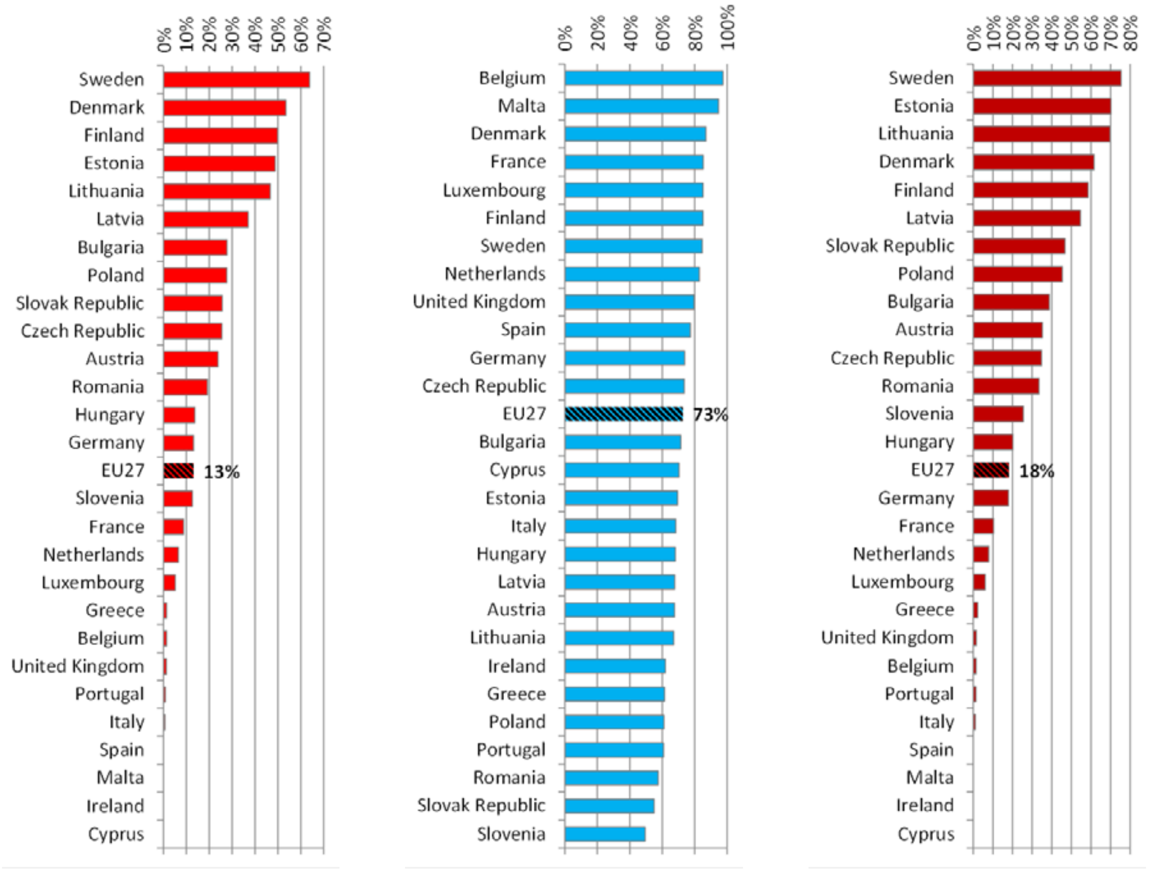

Fig. 3. EU27 and Member State average values in 2010: District heating market shares of total national residential and service sector heat markets (left), urban population shares of total national populations (centre), corresponding district heating market shares of urban residential and service sector heat markets (right). Sources: (Bertoldi et al., 2012; IEA, 2012a; UN, 2010).

Forth, with direct reference to the combined use of publicly open data and energy statistics in this thesis, district heating, and excess heat recovery, has so far never been explicitly visible in international energy statistics since no such entries exist in current templates and queries. This unfortunate circumstance, together with above mentioned general conditions, may in part explain the fact that district heating has remained relatively marginal in the European Union on average (13% of total building heat market in 2010), as also illustrated in Fig. 3 at left.

On a legislative level, the European Union has not failed to recognise the importance of energy efficiency and the systemic benefits of cogeneration and district heating, which has been communicated in a series of directives during only the last decade (EU, 2004, 2008, 2009, 2010a, b). From a policy perspective, however, no coherent plan for large-scale deployment of district heating and excess heat recovery has been conceived – until the launch of the 2012 directive on energy efficiency (EU, 2012, 2013), in which the significance of these measures has been acknowledged by inter alia requesting Member States to perform national assessments of potentials for excess heat recovery and district heating[10]. As will be further demonstrated in this thesis (e.g. in appended Paper VI), generally high shares of urban dwellers among total European population counts, see Fig. 3 at centre, which align well with the dependency on high heat demand densities for feasible heat distribution in district heating systems, provide a basic favourable setting for the success of any such ambition. Additionally, most – but not all – excess heat-generating activities in European energy and industry sectors are currently located in, or in the close vicinity of, towns, cities, and larger urban zones, which further emphasises the viability of these measures. Given the fundamental nature of network heat distribution, it being in principle an urban occurrence, it is relevant to consider district heating heat market shares also as corresponding shares of pure city heat markets (Fig. 3 at right). As can be seen, district heating supplies, on average, approximately every fifth building with energy for space heating and hot water preparation in European cities today.

The full consequence of Europe's well welcomed strategy to increase energy efficiency and reduce primary energy demands by expanding the use of district heating, cogeneration, Waste-to-Energy incineration (WTE), excess heat recovery, etc. represents however a comprehensive redesign of long settled (parallel) supply structures for the heating of buildings. This thesis includes some work (see e.g. Discussion sections in appended Papers III, V, and VI) that addresses the imposed additional energy system complexities that inevitably will accompany the success of such a transition of the European heat market. The challenges associated to a future realisation of highly efficient and synergetic serial supply structures for these energy services, are to some extent technical, of course, but are mainly so also operational, organisational, and economical. Synergetic heat markets, serial supply structures, excess heat recovery, renewable heat resource utilisation, higher integration between heat and power sectors, reduced future heat demands in buildings, heat storages, etc., all facilitated by the core functionality of local district heating (and cooling) systems, are all also challenges to be met by the design, operability, and management of these infrastructures. Several of these challenges and concepts are considered and investigated in this thesis, which has resulted in the following aim and research questions.

1.2 Aim and research questions

The findings put forward in this thesis are interpretable as genuinely supportive of large-scale implementation of district heating and excess heat recovery in future Europe, but it should be made explicit that the objective of this thesis excludes any advocacy or biased sympathy for any specific solutions to the problem at hand. The general objective of this thesis is rather to

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[10] Among most noticeable provisions by this directive, Member States are to: (i) Set indicative national energy efficiency targets in the form they prefer (by 30 April 2013). (ii) Use energy efficiency obligation schemes to achieve certain amounts of energy savings in households, industries, and transport sectors (1 January 2014 to 31 December 2020). (iii) Provide consumers easy and free-of-charge access to data on energy consumption by individual metering. (iv) Meet obligations for large enterprises to carry out energy audits every four years. (v) Ensure 3% annual renovation rate of buildings in public sectors owned and occupied by central governments (1 January, 2014). (vi) Increase efficiency in energy generation: including national assessments for cogeneration and district heating potentials, including recovery of excess heat (by 31 December 2015).

present decisive methodological steps and major results from the studies performed in the appended papers, studies that have all followed basic principles of scientific investigation. By these principles, initial theories and hypotheses, discussed and formulated as possible explanations and solutions for the observed phenomena, have been tested by exposure and comparison to real world conditions. To facilitate such comparisons, collection, processing, and refinement of data, from a rich variety of sources (see section 3 Data for further information), together with the use of available, reformulated, or invented methodological approaches, models, and theoretical concepts, has produced resulting descriptions of these conceived solutions on which basis quantitative and qualitative conclusions have been possible to establish. The primary concern here is thus not to what extent the solutions evaluated here are to be favoured by the future European community, irrespective of their suitability and apparent viability, but just the assurance that whatever pathways are chosen, whatever steps are taken, may their rationale rest on sound and sensible scientific reason.

The general aim of this thesis originates in one of the main research question of the 2007 to 2010 Swedish research project Pathways – Swedish System Solutions[11], the first of three larger research projects in which the appended papers have been performed. The question, which quite sweepingly asked, “To what extent can Europe´s 5000 district heating systems contribute to a sustainable development?”, was broken down into three dedicated issues[12], of which the first two were to result directly in appended Papers I, II, and III, and indirectly so in remaining appended papers. During the course of these studies, this general aim was later refined and reformulated. In my 2011 licentiate thesis (Persson, 2011), it was expressed as:

> *“The central hypothesis of this work is the idea and vision that expanded use of district heating technology can act as a direct counter measure to decrease carbon dioxide emissions from fossil thermal power generation in Europe. By providing viable “bottoming cycles” in the general European energy system, permitting substantial excess heat recovery from currently inefficient central and local conversion processes herein, district heating technology (in close conjunction with cogeneration of heat and power) furthermore represent a structural energy efficiency measure capable of reducing total volumes of primary energy supply while maintaining current final end use levels. An initial premise supporting the realisation of this vision would be that district heating systems are able to provide cost-effective heat distribution in competition with other local heating alternatives on European heat markets”* (p. 4)

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[11] In the original application to the Swedish Energy Agency (STEM), the project description read, “The project is a Swedish add-on project in an extensive European project. Focus will be a number of areas and solutions where Sweden and Swedish research is in a leading position internationally and thus can contribute to new knowledge that is important in the changeover of both the Swedish and European energy systems to sustainability and meeting the climate objectives and also benefit the Swedish export industry. A cross-scientific group of researchers cooperate about six questions at issue, important to the sustainable development; hindrances/possibilities of the juridical system, driving forces and calculation customs for investments, greenhouse gases, district heating/district cooling, energy efficiency, and bio fuels”. See also subsection 1.4 Outline and context for further information.

[12] In short, the first sub question was “How do energy efficiency measures in buildings alter the prerequisites for district heating expansion?” and the second, “To what extent can sequential chains of provision be a pathway to a sustainable development in Europe? If energy is used in several sequential steps with multiple uses, it would be possible to reduce the amount of prime energy”. The third question, partially addressed at the time but never published as a unique study, asked, “How such a sustainable development should be organised with low resource utilization and the demand of simple and continuous delivery on the user-side?”

As such, this description is valid as hypothesis and general aim for this doctoral dissertation thesis as well. In addition, this thesis investigates also total European energy system costs associated to large-scale implementation of district heating (Paper IV), discusses the consequential benefits and effects of higher integration between power and heat sectors obtainable by such an expansion (Paper V), and identifies spatially the geographical locations of strategic heat synergy regions throughout the European continent (Paper VI). Broken down on each appended paper, this general aim transforms into a set of corresponding general research questions which contextualises the unique issues elaborated in each respective paper (for specific and detailed research questions, see introductory sections in corresponding appended papers). As presented below in concentrated form, ordered by logical disposition given contents and findings from each separate study and not chronologically by date of publishing[13], the appended papers focuses on the following significant topics and general research questions:

I. Paper I evaluates the competitiveness of district heating on current European heat markets based on an analytical approach. The paper presents the distribution capital cost model and identifies determining parameters and circumstantial conditions for the assessment of feasibility thresholds for cost-effective heat distribution in district heating systems. On this basis, the future competitiveness of European district heating systems is evaluated in two scenarios of reduced building heat demands. The general research question can be expresses as:

   - What are the current distribution capital cost levels for district heating in European cities and to what cost-effective and directly feasible future district heating heat market shares does these cost levels correspond?

II. Paper II elaborates on the concept of effective width, one of four decisive parameters conditional for reformulating the traditional expression for linear heat density, as performed in Paper I. Of these four parameters, effective width represents an innovative model quantity with little previous representation in the field of district heating research. This paper is complementary to the theoretical framework of Paper I and addresses the general research question:

   - How is the demand for district heating pipe lengths to be determined in a given land area?

III. Paper III analyses the European energy balance with focus on fuel transformations in central conversion and heat demands in the building sector, and introduces new theoretical concepts whereby to characterise and quantify the benefits of excess heat recovery, e.g. heat recovery rate and heat utilisation rate. The principal configuration of serial supply structures, barriers and drivers, are discussed and a comparative analysis of EU27 averages and currently best Member State practises is performed to

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[13] The chosen order is also reflected in the sequence of subsection headings by which the papers are presented and addressed in section 2 Methodology and section 4 Results. In this respect, appended Papers I and II, which emanated from the same study and which are complementary to each other, are presented in unison under a common sub section heading.

assess a plausible European excess heat recovery potential. The paper answers the general research question:

- What general conditions affect a transition from parallel to serial supply structures in Europe and by what quantities can current and future levels of excess heat recovery and utilisation in European district heating systems be expressed and evaluated?

IV. Paper IV models the complete European energy system in 2050 according to the energy efficiency scenario in the European Commission’s report, Energy Roadmap 2050 (EC, 2011a) and compares this to an alternative scenario with 50% district heating in the building heat sector by this year. The methodological approach centres on a combination of simulation modelling and spatial mapping, which inter alia results in the new pan-European heat atlas, regional potentials for excess heat recovery and renewable heat resource utilisation, as well as total energy system costs. No explicit research questions are formulated in the appended paper, but the following general research question captures the essence of this work:

- What are the total energy system cost benefits for future Europe if combining individual energy efficiency measures with large-scale implementation of district heating, as opposed to individual energy efficiency measures alone, in reaching its target of an 80% reduction in annual greenhouse gas emissions in 2050 (compared to 1990 levels)?

V. Paper V reviews the unique Swedish experiences of large-scale heat pumps and electric boilers in district heating systems, i.e. power-to-heat solutions, in view of its relevance for European power grids with higher shares of intermittent renewable electricity supply in the future. The paper is complementary to Paper IV (which foresees an increased demand of such balancing technologies in the 2050 European energy system), raises no explicit research question, but contributes in the context of this thesis to:

- Discuss general implications regarding the balancing role of district heating in highly integrated future energy systems.

VI. Paper VI maps, on regional scale with a European continental scope, geographical locations of building heat demand concentrations, excess heat generating activities in energy and industry sectors, and current cities with district heating systems, to identify strategic heat synergy regions (primary target regions) for large-scale implementation of district heating in future Europe. The paper introduces a reversed calculation sequence by which to assess annual excess heat volumes based on (public) data on carbon dioxide emissions. The general research question most appropriate for this paper is:

- Where, in what regions and at what geographical locations, will large-scale implementation of district heating in future Europe be most cost-effective and suitable based on current conditions?

In retrospective, looking back at the six or so years that have passed since this work began, it is clear that the elucidative findings of Paper I – which, in short, indicates a three-fold directly feasible expansion potential of European district heating from current heat market share levels – constitute the core foundation by which the subsequent studies earned their justification. Would it had been that the distribution capital cost model instead had suggested none or only marginal room for viable extensions and new installations of district heating systems on these heat markets, it would have been futile to go ahead and model district heating expansion potentials and mapping heat synergy regions in future Europe. Consequently, the research presented in this thesis constitutes a well-founded comprehensive toolkit that can be of assistance in the proper evaluation of current and coming opportunities to decarbonise the European heat sector. It should hopefully provide also some suggestions as of how to distinguish between suitability of different solutions, depending on geographical location, energy system perspective etc., all in the important effort not to sub-optimise future supply structures for the heating of buildings. A major challenge extending from this thesis on to local, regional, and national energy planners, policymakers, and governments, is thus to wisely consider where and to what extent different solutions will prove most cost-effective and system-appropriate. One critical criterion by which to carry out such distinctions dwell subtly in the fundamental condition that urban areas, while hosting most expensive buildings to refurbish, provide highest heat demand densities, contain a majority of excess heat generating facilities, and are the natural domains of network heat distribution infrastructures.

1.3 Key assumptions and delimitations

To facilitate the assessment of distribution capital costs per city district in Paper I, it was a model requirement to assume a general 100% connection rate to district heating networks in all 83 studied French, German, Belgian, and Dutch cities, which of course is conceivable only in theory. Other key assumptions in Paper I include that of future city shapes corresponding to those represented by the 2001 Urban Audit database, which may not entirely reflect neither present nor future conditions (albeit current population trends suggest even larger urban population shares in the future). Additional key assumptions in this work include that of district heating companies uniformly applying planned rate of returns represented by the assumed annuity (3%, 30 years), which may differ significantly depending on investment strategies of different actors. Also, used construction cost levels (which are based on Swedish experiences, a mature district heating country), may deviate from corresponding cost levels in novel district heating countries.

In Paper III, all rejected heat from fuel combustion activities and processes in energy and industry sectors, not absorbed as electricity or maintained in industrial products, is assumed available for excess heat recovery. For a wide range of reasons, e.g. practical, thermo-technical, geographical, and economical, viable recovery volumes of present secondary outlet streams may seldom correspond to – but rather be lower than – the plausible potentials estimated herein. In allegory, after a reformulation of this original definition of excess heat in Paper VI, invoked during the peer review process, excess heat came eventually to include “all rejected heat in thermal power generation not absorbed as electricity, and rejected heat in industrial processes not added or maintained in industrial products conceived available for recovery”. Since the objective of none of these studies is to provide site-specific prognoses or local feasibility assessments of available excess heat volumes – but merely to illustrate the full circumference of the energy squander occurring in the present European energy system – corresponding default recovery efficiencies are set to reflect the maximal European excess heat recovery potential, not necessarily the practicable one.

In Paper IV, a key assumption is made with reference to total European building heat demands in 2050, concerning heat demands for both space heating and hot water preparation. In contrast to the energy efficiency scenario in the Energy Roadmap 2050 projection (EU-EE scenario), which perceives a 61% reduction of these heat demands in 2050 (relative projected 2015 levels at 14.5 EJ), the alternative Heat Roadmap Europe energy efficiency scenario (HRE-EE scenario) instead stipulates a decrease of only 34% for the same year. The reasons motivating these assumption are made explicit in sub section 4.1 “Reducing the level of heat savings” in the appended paper. For space heating heat demands, in short, the rationale for suggesting only a 47% reduction (62% in the EU-EE) rests on a comparison to the most ambitious 2050 deep-renovation scenario for heat savings in buildings by EURIMA (the European Insulation Manufacturers Association), in (Boermans et al., 2012), where this reduction level is proposed. For hot water preparation, the EU-EE scenario elaborates on a 55% energy demand reduction between 2010 and 2050, while the Heat Roadmap Europe energy efficiency scenario instead expects an increase of 16% during the same period[14]. Another, conceptual, assumption in this work – in part conditional for the approach itself – is that as end use energy demand reductions in buildings become more expensive as larger heat savings are achieved, it is essential to identify at what total energy system cost levels investments in heat distribution infrastructures becomes more cost-efficient alternatives to reduce total primary energy demands.

In Paper VI, additionally, although the spatial mapping of heat demand concentrations, excess heat activities, and cities with district heating systems, encompasses all 1281 NUTS3 regions located in main land continental EU27 Member States (thus excluding 13 overseas regions, by 2010 NUTS classification), the identification of strategic heat synergy regions is limited to 16 selected Member States. This delimitation is motivated by some Member States being classified as either “Consolidation” (DK, EE, FI, LT, LV, SE) or “Out-of-scope” (CY, EL, ES, MT, PT) countries with respect to current integration levels of district heating on respective national heat markets. All 63 strategic heat synergy regions identified in this process thus belong to Member States either in classification categories “New Development” (BE, IE, LU, NL, UK (18)), “Expansion” (AT, DE, FR, IT, SI (22)), or “Refurbishment” (BG, CZ, HU, PL, RO, SK (23)). In this paper, further, the basis for calculated annual excess heat volumes from Waste-to-Energy incineration facilities deviate from the general approach of using site-specific annual carbon dioxide emission data. Instead, a separate investigation of 410 dedicated Waste-to-Energy plants provided data on currently installed incineration capacities, which, in combination with an anticipated average energy content of waste at 10.3 MJ/kg (CEWEP, 2013), facilitated the estimation of annual excess heat volumes from current European waste incineration.

A general delimitation of this work is the exclusion of district cooling systems. For this reason, no specific investment cost calculations for district cooling systems, no assessments of cool demands in buildings, and no spatial mapping of cool synergy regions are included in this work. District cooling, however, is part of the energy system modelling in Paper IV, where the EU27 building cool demand is anticipated (15% of the current heat demand). District cooling systems are assumed to provide 20% of this demand in 2050 (10% in 2030).

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[14] The motivation for this assumption includes five main aspects: (i) Expected population growth in Europe of 3.2% between 2010 and 2050. (ii) Hot water use per capita anticipated to increase during the same period. (iii) Reduced occupants per dwelling, i.e. more single households in the future. (iv) Additional new heat demands for hot water preparation as regions with currently limited access to such energy services become wealthier. (v) Expected growth of European building areas between 2015 and 2050 (residential: 32%, non-residential: 42%).

1.4 Outline and context

The disposition of this thesis, which consists of this introductory essay and the appended papers, is structured so that the outline of the essay corresponds to the order by which the associated papers are appended. This structure is most pronounced regarding the order of subsections in section 2 Methodology and section 4 Results, where the numbering of corresponding sub section headings reflect the numbering of the appended papers. Appended Papers I and II are in this respect addressed together. The outline and disposition of the essay is deliberately also arranged in line with a common journal article format, where section 1 Introduction aims to position the included studies in a wider context, present overarching research challenges associated to this work, and specify the thesis' aim and general research questions. In following sections 2 Methodology, 3 Data, and 4 Results, the aim is not to account in detail for the complete contents of the appended papers, but to highlight significant and most important approaches, sources, and findings relevant for the perspective held throughout the essay and for the contextual understanding of the reader. In sections 5 Discussion the study results are reflected upon and evaluated in view of implications and relevance related to the wider context presented in the introductory section, while section 6 Conclusions, presents answers to the initially raised general research questions. Some future research issues extending from this work are finally addressed in section 7 Future research.

The work described in this thesis relates to three larger research projects, during the years between 2008 and 2014, in which the included studies were performed. The first of these, as briefly mentioned above, the Pathways – Swedish Systems Solutions project (2007-2010), financed by the Swedish Energy Agency, was a parallel project to the international Alliance for Global Sustainability project Pathways to Sustainable European Energy Systems, hosted by the Department of Energy & Environment at Chalmers University of Technology in Gothenburg, Sweden. The research performed within the two projects was carried out in cooperation under the common aim to develop modelling tools able to outline and evaluate viable courses of transition – pathways – for the European energy system to meet sustainability targets in the fields of energy efficiency, carbon dioxide emission reductions, and increased use of renewable energy sources. Appended Papers I, II, and III, as well as two book chapters in (AGS, 2011a, b), originate in this project.

The prelude to the second research project, The Heat Roadmap Europe project (HRE, 2014), included two pre-studies for the EU27 (Connolly et al., 2013; Connolly et al., 2012b), both partly financed by Euroheat & Power in Brussels, in which the central methodological idea to combine energy system modelling with geographical information systems (GIS) mapping of local conditions was first applied on a continental scale for Europe. The pre-studies were performed in collaboration mainly between researchers from the Department of Development and Planning at Aalborg University in Denmark and researchers from the School of Business and Engineering at Halmstad University in Sweden. During the course of the two pre-studies (2012-2013), it was agreed among the participants to document the study approach and findings in journal publications as well. Appended Papers IV and VI constitute these academic documentations (albeit updated versions with respect to study years and associated data), and the project concept has subsequently extended into the current Intelligent Energy Europe (IEE) project Stratego (Stratego, 2014). The Stratego project (2014-2016) consists of a consortium of 16 European partners and aims to provide enhanced heating and cooling plans for a number of local regions and cities as well as on national scale for the Czech Republic, Croatia, Italy, Romania, and the United Kingdom.

The third research project in which the presented work has emanated is the Strategic Research Centre for 4th Generation District Heating Technologies and Systems (4DH) at Aalborg University in Denmark (4DH, 2014). The project, which will be active for a six-year period between 2012 and 2017, is partly financed by the Danish Council for Strategic Research and partly by a consortium of industrial partners and district heating companies. The aim of this international research centre is to assist in the development of 4th generation district heating technologies and systems, as district heating – in co-existence with substantial energy savings and conservation measures in the future heat demand – has potential for playing an important role in terms of increasing energy system efficiencies by utilisation of excess and renewable heat resources. The scientific objective is to establish a platform, in which synergy is created between the development of grids and components, house installations, district heating production technologies, system integration, planning and implementation tools, as well as the development of methodologies and analytical approaches. In all, the project includes 13 PhD positions in total, where research project 2.4 "Low-temperature energy sources for district heating" is associated with the work presented in appended Paper V.

During the course of this work, additional funding and project participation include also the 2011 to 2014 project Toward 4th Generation District Heating, an Annex X project of the IEA (International Energy Agency) Implementing Agreement on District Heating and Cooling, including the integration of Combined Heat and Power (Rosa et al., 2014). This project was performed in collaboration by five project partners[15] and aimed to collect information and data on early examples of low temperature/low energy district heating systems around the world today, as well as to discuss the concept of 4th generation district heating to stimulate future research, development, and implementation of these systems. Complementary financial support, finally, was also received from Fjärrsyn, the Swedish district heating research programme (through the District Heating within the Energy System project), and from the School of Business and Engineering at Halmstad University, Sweden.

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[15] Technical University of Denmark (project leader and editor), Halmstad University (Sweden), Dresden University of Technology (Germany), Scottish & Southern Energy (United Kingdom), and the Building Research Establishment (United Kingdom).

2 Methodology

In this section, methodological approaches from the six appended papers are described with focus on key concepts and conditions. The intention is to concentrate mainly on most significant steps and aspects, while the full detail can be found in corresponding method sections in each of the appended papers. In general, the overarching methodological approach in this work is permeated by two main ideas; the use of publicly available data together with energy statistics to characterise European heat markets and associated district heating potentials, and the combined use of energy system modelling and geographical mapping of local conditions. In terms of viability, this approach requires, among other things, the development of appropriate theoretical concepts and applicable relations to allow the different types of data and perspectives to be linked and made compatible. In this section, additionally, as also indicated above, the order of the sub sections presented below corresponds to that by which the appended paper are numbered and attached to this thesis. For this reason, this section starts with 2.1 Cost of heat distribution (Paper I and II), and continues with 2.2 Serial supply structures (Paper III), 2.3 Energy system modelling (Paper IV), 2.4 Integrating heat and power sectors (Paper V), and 2.5 Spatial mapping (Paper VI). Original literature and data references from the appended papers are included if considered relevant, but the ambition is not to account for the entirety of these sources in this context.

2.1 Cost of heat distribution

A basic premise for evaluating the competitiveness of district heating systems on competitive heat markets, given that heat customers prefer the least costly alternative, is that the total customer cost for district heat needs to be lower than the cost of any other local heating alternative. Unlike most such alternatives (natural gas, electricity, biomass etc.), for which the main operational cost is the expenditure for the heat generation itself, the total customer cost of district heat consist of a corresponding heat generation cost, but also a heat demand density dependent and network characteristic heat distribution cost, as principally outlined in Fig. 4. The competitiveness and cost-effectiveness of district heating systems hereby depends on a balance between heat demand concentrations on one hand (population and heat demand densities of any land area to be provided), and total network investment costs on the other hand (construction cost levels and economical investment conditions). From this, the existence of feasibility thresholds, e.g. required minimum levels of heat demand concentrations at given investment capacities, could be expected.

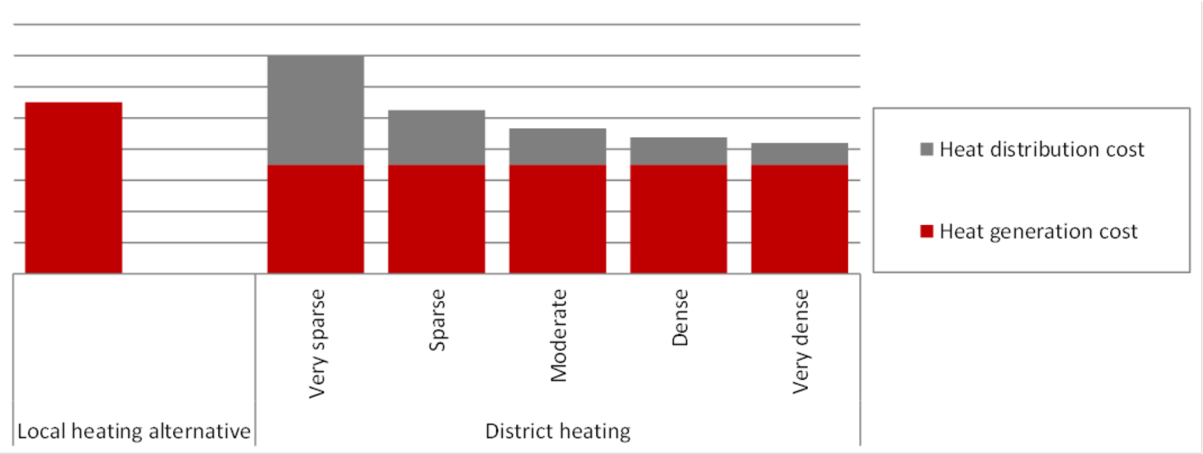

Fig. 4. Principal comparison of total customer costs for local heat generation alternatives and district heating, with regard to the heat generation cost and the heat demand density dependent heat distribution cost (appended Paper I).

The identification of such feasibility thresholds, together with anticipated heat distribution capital cost levels at such thresholds, therefore constitutes relevant parameters for the evaluation of feasible expansion potentials for district heating on European heat markets. However, the few previous attempts of estimating or determining the relation between investment costs for district heating systems relative heat demand densities, identified when reviewing literature on the subject (Brachetti, 1984; Schulz, 1933; Simon, 1950), had relied primarily on empirical information from existing and operating networks, thus not on systematic analytical approaches. To facilitate such an analytical analysis – a prerequisite if to assess investment conditions for district heating system at new locations with no heat distribution networks currently in place – it was necessary to perform a theoretical reformulation of the traditional expression for linear heat density (Q_S/L) (Frederiksen and Werner, 1993), as shown in eq. 1:

$$\frac{Q_S}{L} = p \cdot \alpha \cdot q \cdot w = e \cdot q \cdot w \qquad \text{[GJ/m]} \qquad (1)$$

Since linear heat density, a denominator term in the expression for the distribution capital cost (see eq. 3), cannot be empirically established for systems yet to be built (since neither annually sold heat (Q_S) nor the length of the piping network (L) are known), this initial theoretical approach was essential for assessing plausible future district heat locations. As such, the theoretical reformulation enables calculations and modelling of district heat distribution capital costs using alternative data categories (population density (p), specific building space (α), specific heat demand (q), and effective width (w)), that are either publicly available or otherwise retrievable from energy statistical sources. The plot ratio (e), a traditional city planning quantity expressing the fraction of total building space area in a given land area[16] (Statens Planverk, 1985), is an important parameter in the methodology associated with the distribution capital cost model. Partly so because it allows the establishment of feasibility thresholds for cost-effective heat distribution as a function of population and heat demand densities, partly so because it is used as independent variable in model calculations of effective width, and partly so by its applicability to sort investigated city districts[17] into different categories of area characteristics. As detailed in Table 1, the distribution capital cost model designates construction cost levels (C_1 and C_2), reflecting unique investment cost level conditions by categories; inner city areas, outer city areas, and park areas, to city districts in accordance with their category belonging. In the context of appended Paper I, the used construction cost levels are gathered from Swedish experiences, assembled in (SDHA, 2007), and converted to Euro by a currency exchange rate of 10.8 SEK/€.

Table 1. Categories of area characteristics, corresponding plot ratio levels, and associated construction cost levels in appended Paper I

Area characteristics	Plot ratio (e)	C_1 [€/m]	C_2 [€/m^2]
Inner city areas	$e \geq 0.5$	286	2022
Outer city areas	$0.3 \leq e < 0.5$	214	1725
Park areas	$0 \leq e < 0.3$	151	1378

While linear heat density indicates the utilisation level of a district heating system, i.e. the amount of heat delivered per unit pipe length, the last of the four alternative data categories, effective width (w), indicates the physical coverage of the heat distribution network relative a

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[16] The plot ratio may alternatively be expressed also as the product of population density (capita/km^2) and specific building space (m^2/capita), given the sum is divided by a factor 10^6 (see also Fig. 6).

[17] One thousand seven-hundred and three city districts in 83 French (826), German (632), Belgian (84), and Dutch (161) cities are included in the assessments performed in appended Paper I. See section 4.1 Feasible expansion potential in urban areas for further information.

given land area. Hereby, effective width, which represents a novel and innovative model quantity in the field of district heating research introduced by Werner in (Werner, 1997), is a measure indicating the district heating network extension level within a given land area. Reversibly, given that actual effective width values and land areas are known, effective width allows estimations of the relative demand for pipe lengths in new district heating systems. For the calculations in appended Paper I, a power function with effective width as dependent variable and plot ratio as independent variable was established based on results from studies on district heating systems in 39 detached house districts (Netterberg and Isaksson, 2009) and 34 multi-family housing district (Larsson et al., 2002) in Sweden. This relation is expressed in eq. 2 below and is further detailed in appended Paper II (Note that (e) refers to the plot ratio value, not to the natural logarithm base):

$$w = 61.8 \cdot e^{-0.15} \qquad [\mathrm{m}] \qquad (2)$$

Apart from these model functions, effective width serves yet another purpose in the distribution capital cost model. Since the model relies on aggregated data on total city district land areas, hence not subtracting portions of these consisting of areas never to be targeted by district heat deliveries (e.g. green areas, waterways etc.), assessments of heat distribution capital cost by use of such geographical information may be hazardous in low plot ratio areas. If settlements in low plot ratio land areas are concentrated to certain parts of the total land area, as opposed to being widely distributed, there is a risk that the model overestimates actual network investment costs since they are related to the complete land area at hand. Fig. 5 illustrates this situation. In the distribution capital cost model, effective width acts as a corrective mechanism in these instances.

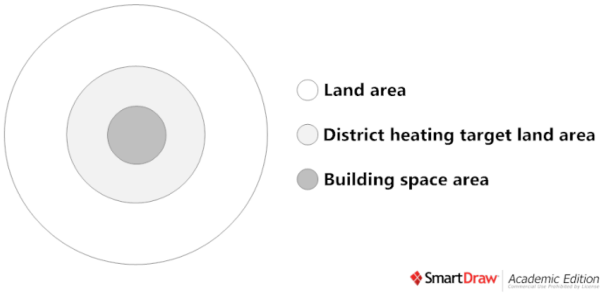

Fig. 5. Low plot ratio land area. Total city district land area (retrievable from open data source) and portion of land area targeted by district heat distribution. Appended Paper II.

To arrive at the distribution capital cost[18], i.e. the annualised cost of the total network investment cost (I), the distribution capital cost model utilises the above-described theoretical reformulation of linear heat density in combination with the derived construction cost levels, average pipe diameters (d_a)[19], and assumptions on general economic investment conditions. For the latter, an annuity (a), chosen to reflect a long-term investment strategy in order to obtain the benefits of district heating in the future, was established based on a real interest rate of 3%, along with a 30 year investment lifetime for European district heating networks. By this procedure, the annual distribution capital cost can be written as:

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[18] The heat distribution cost includes also additional operational expenditures to compensate for temperature and pressure losses associated with network heat distribution, as well as maintenance costs. The distribution capital cost, however, is estimated to constitute the major cost component in the total heat distribution cost.

[19] One hundred and thirty-four observations of average pipe diameters relative linear heat densities in Swedish district heating systems are used to establish a logarithmic function for the model calculations. See appended Paper I for further details.

$$C_d = \frac{a \cdot I}{Q_S} = \frac{a \cdot (C_1 + C_2 \cdot d_a)}{p \cdot \alpha \cdot q \cdot w} \qquad [€/GJ] \qquad (3)$$

In the distribution capital cost model, the four numerator terms and the four denominator terms in eq. 3 together constitute eight independent input data parameters facilitating model operability. Each of the four new denominator terms has its own purport. Firstly, the population density indicates the amount of people living in the land area to be analysed. Secondly, the specific building space provides the amount of building space available in the land area, i.e. number of heated square meters per capita (residential as such, but by a factor 1.4 increased in appended Paper I to include service sector buildings as well (value interval herein between 49-56 m^2/capita)). Thirdly, the specific heat demand quantifies the amount of heat needed in order to provide space heating and domestic hot water preparation in these buildings (average value of 0.50 GJ/m^2a in appended Paper I). Fourthly, the effective width provides information about required pipe lengths of the district heating systems conceived to heat these buildings. As outlined in Fig. 6, the model calculates on this basis four intermediate input data quantities, of which the specific investment cost (annual amount of investment per meter piping) and the linear heat density generates the final output. The distribution capital cost hereby provides a quantified value of the annual capital cost for heat distribution in a district heating system, relative the volume of annual heat deliveries in the system.

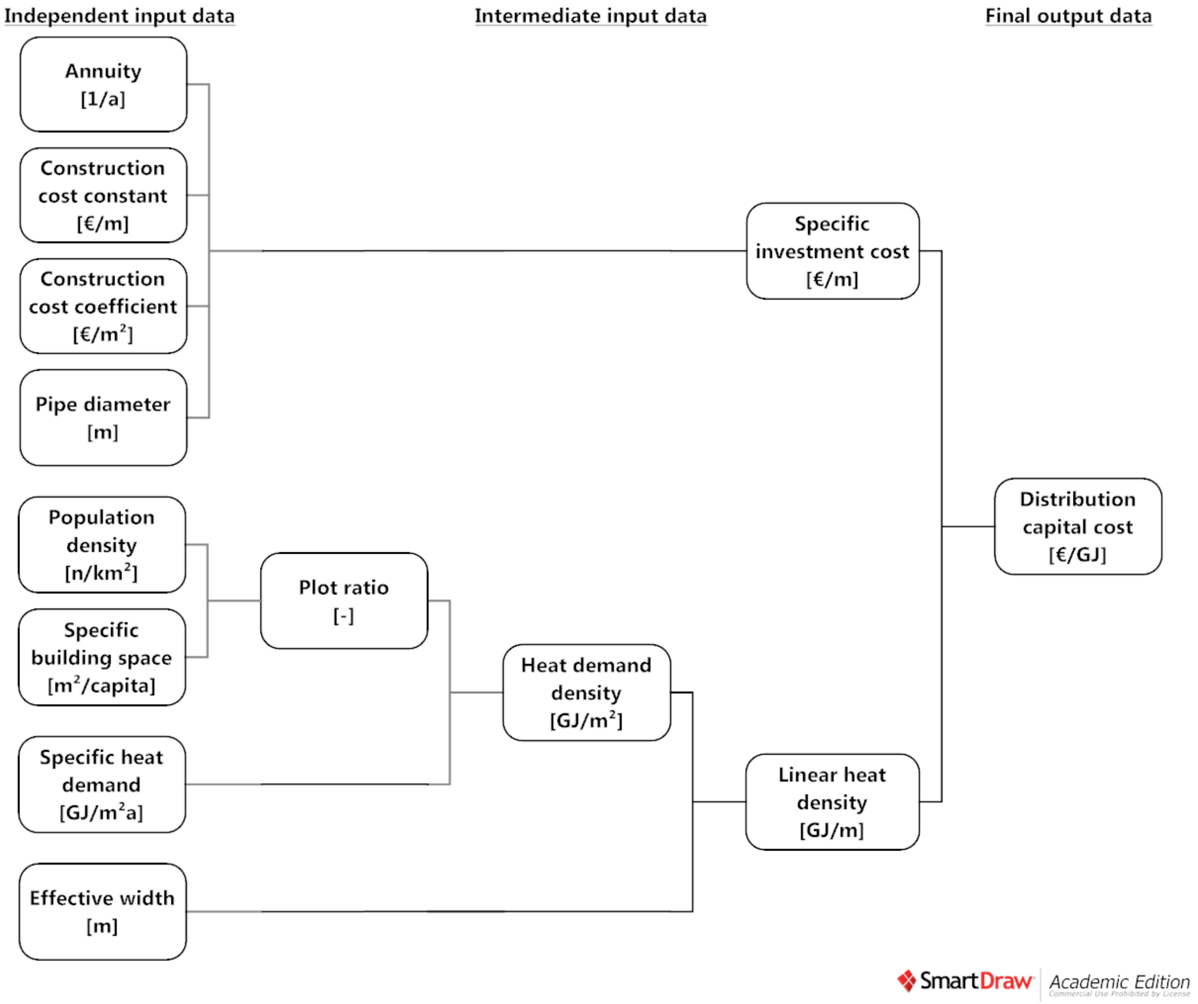

Fig. 6. Graphical description of the distribution capital cost model in appended Paper I. Independent input data parameters (left), intermediate input data parameters (centre), and final model output parameter in right column.

2.2 Serial supply structures

The concept of serial supply structures originates in the idea of sequential energy supply, which in contrast to the parallel fuel supply structures characterising the fossil era – where each activity converts primary energy separately and often with only partial use of the fuel energy content – is characterised by optimal resource utilisation mainly by efficient use of secondary heat. A serial supply structure reduces total primary energy demands for the sum of processes engaged in the synergy chain, since energy demanding processes downstream the chain are (fully or partially) supplied with excess energy from a previous step (also known as energy cascading). This concept may be incorporated as a technology system property in itself, as e.g. in cogeneration plants, where excess heat from primary energy inputs is made useful in design-intended serial steps[20]. But the concept may also extend beyond the designed features of a unique technology system and provide excess heat from a wide variety of heat generating activities to buildings and industrial processes – excess heat that most likely otherwise would be wasted. At the end of a serial supply structure, thus, low temperature excess heat may be recovered and distributed in district heating systems to substitute other fuels used for heating purposes. Hereby, sequential energy supply represents a structural energy efficiency measure, rather than just a technical one, and the organisation and operation of such synergetic supply structures imposes as well technical as non-technical issues to address.

In the context of appended Paper III, both a quantitative and a qualitative approach are used. In the first approach, which aims at describing current levels of excess heat recovery and utilisation in Europe today and compare EU27 average values to currently best Member State practises[21], five theoretical concepts are developed to facilitate such an evaluation. In short, these concepts: absorption efficiency (η_{abs}), recovery efficiency (η_{heat}), total conversion efficiency ($\eta_{tot,}$), heat recovery rate (ζ_{heat}), and heat utilisation rate (ξ_{heat}), are established based on conventional laws of thermodynamics. In analogy with the Carnot efficiency, where a primary heat input (Q_{in}) equals the sum of generated mechanical work (W) and rejected heat output (Q_{out}), if considered conservative and neglecting dissipation by e.g. friction or distributive losses, this basic relation is expressed by the vocabulary of this work as:

$$E_{prim} = E_{abs} + E_{excess} \qquad [\mathrm{J}] \qquad (4)$$

Where the primary energy input (E_{prim}) is the sum of energy absorbed in primary products (E_{abs}) and rejected excess heat (E_{excess}). In thermal power generation, absorbed energy is considered equal to the electrical energy leaving the conversion site, while in industrial processes, the absorbed energy expresses the energy added or maintained in the industrial products leaving the conversion site. The conversion efficiencies associated to the absorption and recovery energy quantities are analogously expressed as in eq. 5 (absorption efficiency) and eq. 6 (recovery efficiency) respectively:

$$\eta_{abs} = \frac{E_{abs}}{E_{prim}} \qquad [\%] \qquad (5)$$

---

[20] As an average assessment, cogeneration reduces primary energy demands by 25%-50% compared to separated electricity and heat-only generation of the same useful units, and represents an efficient and sustainable energy technology in itself (IEA, 2009).

[21] The objective by performing this comparison is to estimate potentials for excess heat recovery and utilisation in future European district heating systems, focusing explicitly on three categories of excess heat activities: thermal power generation, Waste-to-Energy incineration of municipal solid waste, and energy intensive industrial processes.

$$\eta_{heat} = \frac{E_{heat}}{E_{prim}} \qquad [\%] \qquad (6)$$

Recovered excess heat, here symbolised by E_{heat}, represents in the context of appended Paper III, statistically derived volumes of recovered cogeneration secondary heat flows from main activity and autoproducer facilities in district heat deliveries for the year 2008 (IEA, 2010). By this, the total conversion efficiency, describing the full share of useful secondary energy extracted from original primary energy inputs, can be establish as the sum of the two conversion efficiencies in eq. 5 and eq. 6. Finally, in the search of appropriate quantities to express (i) the saturation level of excess heat recovery relative available excess heat volumes, and (ii) the utilisation level of these excess heat recoveries relative to total building heat demands, the recovery rate is defined in analogy with its similar use regarding recycling of paper and cardboard materials (Frankx et al., 2008), according to:

$$\zeta_{heat} = \frac{E_{heat}}{E_{excess}} = \frac{E_{heat}}{(E_{prim} - E_{abs})} \qquad [\%] \qquad (7)$$

The heat recovery rate measures in this sense the success with which the energy system is able to recover excess heat from the excess heat stream and hence provides an indication as of to what extent serial supply structures has been obtained. Complementary, the heat utilisation rate, which is also defined similarly to its use in the paper and pulp sector context, reveals the extent by which recovered excess heat is used to satisfy present heat demands and hence replacing other heat supply:

$$\xi_{heat} = \frac{E_{heat}}{Q_{tot}} \qquad [\%] \qquad (8)$$

The term Q_{tot} (J) refers in appended Paper III to Member State total heat demands in residential and service sector buildings (including hot water preparation) for the year 2008. Given another study objective, however, the utilisation rate could be established according to any appropriate heat demand. Based on these theoretical concepts, essentially, and EU27 and Member State level information from several different sources on relevant energy statistics (Bertoldi and Atanasiu, 2007; EC, 1982; ES, 2010a, b; IEA, 2010; SDHA, 2010; Statistics Sweden, 2010), the study characterises the energy systemic benefits of increased excess heat recoveries in district heating systems and establishes theoretical and plausible potentials for serial supply structures in future Europe.

In the second approach, seven non-technical general conditions[22], acting as drivers and/or barriers for a transition towards increased sequential energy supplies in Europe, are discussed mainly based on a literature review (Cronholm and Saxe, 2009; Grönkvist and Sandberg, 2006; Jacobsen, 2006; Larsson, 2006; Russell, 1994; Rüdig, 1986a, b; Thollander et al., 2010; Unterwurzacher, 1992; Upham and Jones, 2012). The main rationale for this discussion is that a transition from parallel to serial supply structures, i.e. large-scale implementation of district heating, exceeds pure technical aspects of energy technology and heat distribution. In fact, it implies a comprehensive shift in our traditional understanding of organisational structures, investment patterns, and benefit allocation principles within social and industrial institutions in general – and of those in energy system operation and planning in particular.

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[22] Infrastructure investments in district heating networks, collaboration agreements, maintained value chains, policy support, world market energy prices, allocation of synergy benefits, and local initiatives.

2.3 Energy system modelling

The key methodological approach in the Heat Roadmap Europe project, in itself the conceptual foundation from which the complete project emanated, is the idea to combine mapping of local/regional conditions with energy system modelling at high geographical and temporal resolution respectively. This (new) approach earned its motivation mainly from the unfortunate circumstance that district heating and excess heat recovery had received little or only marginal recognition as a potent decarbonisation alternative in a series of contemporary forecasts, projections, and reports aiming to identify pathways for the future European energy system (BPIE, 2011; EC, 2011a; ECF, 2010; Ecofys, 2011; EREC, 2010; Eurelectric, 2010; EWEA, 2011; Fraunhofer, 2012; IEA, 2012b; WEC, 2007). In one of these, the Energy Roadmap 2050 of the European Commission (EC, 2011a), national level projections relying on the PRIMES model (a market equilibrium simulation tool (Capros et al., 2012a, b; Connolly et al., 2010a)), included indeed analyses with quantified current and future building heat demands and represented as well cogeneration as an important technology in the years to come. District heating, on the other hand, was considered an expandable option essentially in the industry sector only. The PRIMES model, however, had not considered genuinely local conditions, which, as mentioned above, constitute the natural domain of district heating and excess heat recovery, why it appeared reasonable to question whether the coverage of the six future scenarios in the Energy Roadmap 2050 report fully reflected all available options.

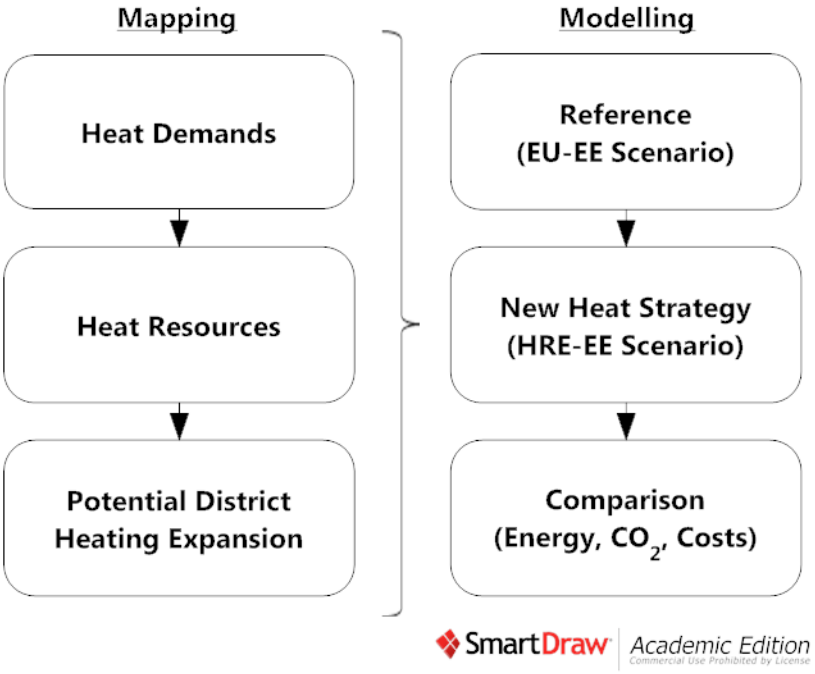

Fig. 7. Central methodological approach of the Heat Roadmap Europe project (appended Papers IV and VI). GIS mapping of local conditions in combination with energy system modelling to facilitate an alternative new heat strategy for Europe (the HRE-EE scenario).

In the Heat Roadmap Europe approach, as outlined in Fig. 7, GIS mapping of unique local European heat demand concentrations, excess heat and renewable heat resource availabilities, and potential district heating expansions, generates regional specific information that feeds into the energy system modelling to produce an alternative heat strategy for Europe – an alternative strategy taking into consideration local possibilities. To acquire this information, which in itself not is directly retrievable from any national level statistical sources, a comprehensive methodological framework of its own was developed in the project. For the first objective, the mapping of unique local heat demand concentrations, the approach generated results at regional level used for regional analysis (see sub section 2.5 Spatial mapping for information on regional level analysis and excess heat ratio, $\xi_{heat,o}$), as well as spatial characterisation of heat demand distributions, i.e. heat demand density at square kilometre grid cell resolution. By such quantifications, derived levels of building heat demand concentration in any given grid cell makes it possible to distinguish coherent areas suitable for district heating expansions, as well as to identify and discard areas not suitable for network heat distribution. Conceptually, this was plausible since the quantity of heat demand density (q_L) is an integral part of the theoretical reformulation of linear heat density performed in appended Paper I (although never made explicit in the context of eq. 1. See also Fig. 6). In analogy, the heat demand density can be written as:

$$q_L = p \cdot \alpha \cdot q \qquad [\mathrm{GJ/m^2}] \qquad (9)$$

If able to establish the heat demand density for any given land area, by consequently multiplying the population density (p), the specific building space (α), and the specific heat demand (q) characterising this land area, the only remaining information required to estimate the linear heat density is effective width (w). Since eq. 2 suggest that for any plot ratio value, a corresponding effective width value is available (at a plot ratio of one the effective width is 61.8 meters), the heat demand density is a key to unlock assessments of investment feasibility for district heating systems at uniform spatial entities[23]. In the context of this work, building heat demands was characterised initially in a top-down manner, where national level energy statistics (IEA, 2010) was used to calculate Member State average per-capita heat demands, subsequently associated to total population counts within each NUTS3 region in respective country (ES, 2012b). Per-capita heat demands by country include the levels of energy services available, such as amount of floor space and indoor climatic comfort levels. It also indicates the technological level of heating, reflected by level of insulation, occupant behaviour, or access to thermostatic control. Moreover, the general climate of each Member State was represented by use of the European Heating Index (EHI), a concept presented by Werner (Werner, 2006), in order to map regional deviations from national and European heat demand averages. To achieve the highest possible resolution for mapping heat demand densities, the GEOSTAT European population grid by GISCO (the European Forum for Geostatistics), containing the 2006 EU27 population density distribution by one square kilometre grid cells (GISCO, 2012), was used to associate established per-capita heat demands per NUTS3 regions to associated population counts per grid cells.

The square kilometre population density raster now containing the heat demand densities per grid cell (raw densities), does however not in itself contain information of larger land areas or regions with similar heat demand levels, which could be the basis for general assessments of coherent district heating potentials by heat demand density. To address this issue, a statistical function available in the ArcMap spatial analyst toolkit (focal statistics, see section 2.5 Spatial mapping for GIS source references), was used to calculate the average values of heat demand densities within a radius of one kilometre from each grid cell. Hereby, a mean heat demand density value (focal mean), necessary to describe the distribution of heat demand densities over larger land areas, was established as a complement to the raw density. Both these heat demand density assessments for EU27 are illustrated, by cumulative heat demand, in Fig. 8.

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[23] In the context of appended Paper I, linear heat densities are established based on all but uniformly sized city district land areas, why the resulting distribution capital costs are associated to unique city districts and not to evenly distributed grid cells of a raster division.

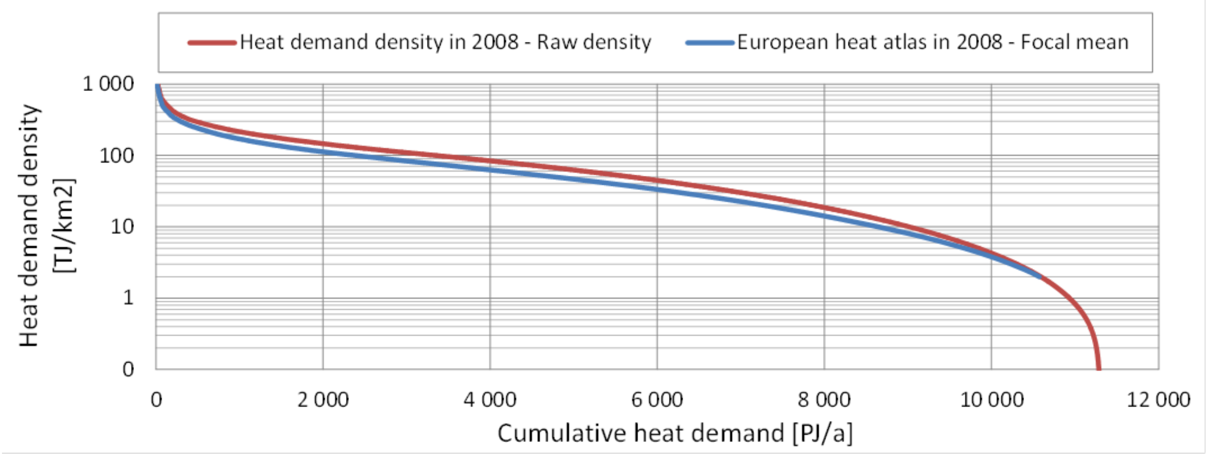

Fig. 8. Cumulative heat demand by heat demand density calculated by square kilometre grid cells, for EU27 in 2008 (appended Paper IV).

It was found through the analysis that the focal mean density method had a levelling effect and resulted in lower overall heat demand density values, somewhat underestimating district heating expansion potentials. If using the raw density values on the other hand, the potential might have been slightly overestimated since many small areas and/or single grid cells with high heat demand densities not located in vicinity of larger prospective district heating areas were identified. It was eventually settled that a plausible solution was to consider the focal mean heat demand density and the raw heat demand density as lower and upper thresholds defining an interval, within which the realistic potential could be found. The main result from this part of the study was a smoothed heat demand density map covering the entirety of the European continent, utilising the focal mean assessment. This pan-European heat atlas appeared furthermore, by the time it was first published (Connolly et al., 2013)), to have had only one predecessor in the field of district heating or energy systems research in Europe, namely the pioneering 2012 assessments by Gils (2012). (See Appendix IV for the full map and Fig. 13 in section 3.2 Energy statistics for a detail of heat demand density in the region surrounding the Finnish capitol city Helsinki).

Based on a classification by Werner, four zones of heat demand density (below 15 TJ/km^2, 15-50 TJ/km^2, 50-150 TJ/km^2, and above 150 TJ/km^2), representing levels of technological development and general feasibility, was also used to classify the nearly two million grid cells constituting the raster. As can be seen in Table 2, where total building heat demands in all inhabited land areas of EU27 are divided into these four heat demand density classes, 68% of current heat demands are found in above 15 TJ/km^2 locations (corresponding to 65% of the total population). Moderate and highly feasible conditions for network heat distribution (above 50 TJ/km^2 at current conditions and referring to conventional 3rd generation technology) represent 41% of the total heat demand but no more than 2.3% of the land area.

Table 2. Heat demand density for EU27 in 2008 by four heat demand density classes representing levels of technological development and general feasibility for district heating expansions

q_L class [TJ/km^2]	P [Mn]	Share of P [%]	A_L inhabited [km^2]	Share of A_L inhabited [%]	Avg. q_L [TJ/km^2]	Q_{tot} [PJ/a]	Share of Q_{tot} [%]
zero	22.6	4	114,924	5.9	1.9	221	2
0 - 15	155.7	31	1,665,529	85.6	2.0	3349	30
15 - 50	127.4	25	121,494	6.2	25.0	3051	27
50 - 150	143.3	29	39,403	2.0	87.0	3436	30
> 150	53.7	11	5111	0.3	243.0	1241	11
Total	**502.6**	**100**	**1,946,461**	**100**		**11,298**	**100**

The energy system modelling part of the Heat Roadmap Europe approach uses the EnergyPLAN Energy System Analysis Model (Connolly et al., 2010b; Connolly and Mathiesen, 2014; Lund, 2008, 2014), for the modelling of current and future energy scenarios for Europe. EnergyPLAN is an input/output energy systems analysis model developed at Aalborg University since 1999 specifically designed for regional and national energy planning. The model is deterministic and aims to identify optimal energy system designs and operation strategies using hourly simulations over one-year periods, and is able to analyse national energy systems on an aggregated basis while identifying potential synergies between different subsectors. By this coverage and configuration, the model involves thermal, electrical, and gas grids, as well as a wide range of cross-sector technologies such as heat pumps, cogeneration, electrolysers, electric vehicles etc. The model is a freeware (available at (AAU, 2014)) and has been used in a wide range of previous studies analysing e.g. the role of district heating at national levels (Connolly et al., 2011; DESIRE, 2010; Lund and Munster, 2003; Lund et al., 2010; Mathiesen et al., 2011), at local levels (Connolly et al., 2012a; Østergaard, 2013; Østergaard and Lund, 2011; Østergaard et al., 2010), and as integral parts of energy systems with high shares of renewable energy sources (Lund, 2005; Lund and Clark, 2002; Lund and Mathiesen, 2009; Lund and Ostergaard, 2000; Lund and Salgi, 2009).

The modelling approach includes first to create a replica of the EU27 energy system based on the Energy Efficiency scenario (EU-EE scenario) proposed by the European Commission in the Energy Roadmap 2050 report (EC, 2011a), both at current conditions (to calibrate the energy system model) and at projected 2050 conditions, as outlined in Table 3. In this table, the original EU-EE energy efficiency scenario for 2050, with a total primary energy supply anticipated at 41.4 EJ/a (11,501 TWh/a), is presented in parallel with the corresponding scenario modelled in EnergyPlan (total primary energy supply of 42.5 EJ/a (11.816 TWh/a)). In accordance with the key assumption mentioned in section 1.3 Key assumptions and delimitations, the deliberate study objective was then to convert from an individual heating bias (61% heat demand reductions from individual energy efficiency measures by 2050 in the EU-EE scenario) to construct a new heat strategy based on the cost-optimal combination of individual and structural energy efficiency measures. Consequently, the conceived Heat Roadmap Europe energy efficiency scenario (HRE-EE scenario) elaborates on a building heat demand decrease of only 34% (which is still substantial), while suggesting a shift from increasingly expensive investments in individual energy efficiency measures as cost-effective market saturation is reached, to investments instead in district heating systems.

Secondly, based on results and input from the mapping part (heat demands, heat resources, and potentials for cost-effective expansions of district heating systems at regional, national, and EU27 average levels), a 50% district heating heat market share in the 2050 European energy system was modelled in the HRE-EE scenario. In the final step, this future projection of large-scale implementation of district heating was compared and evaluated with the original EU-EE scenario in terms of total primary energy supplies, total energy system (and building heat sector) costs, as well as total carbon dioxide emissions. The main purpose of this energy systems analysis was to provide a quantitative comparison between the two scenarios, and especially to quantify the impact that expansion of district heating may have on the future European energy system. By applying energy efficiency measures on both the demand and supply side of the energy system, as is the emphasised case in the HRE-EE scenario, the additional investment costs for heat distribution infrastructures necessary to achieve this objective, are balanced by the possibility to utilise more excess heat from thermal power generation plants, energy intensive industries, and Waste-to-Energy facilities. Hereby, more renewable energy sources such as wind power, biomass, large-scale solar thermal heat, and geothermal heat are also integrated into the energy system.

Table 3. Breakdown of the Energy Roadmap 2050 energy efficiency scenario (EU-EE scenario) for the year 2050. Data values from the original projections, values outlining how these were interpreted to create the reference, and finally the resulting values created by the EnergyPLAN energy system model (appended Paper IV)

Unit	**Year**	**2050 Energy Efficiency Scenario**		
[TWh]	Data	Original	Reference	EnergyPLAN
Demands	Electricity	3204	4281	4281
	Plus additional losses	*1077*		
	Including electric heating	*281*	281	281
	Including electric cooling	*163*	163	163
	District heating for residential and services	159	159	180
	Plus additional losses		21	
	District heating for industry	703	703	793
	Plus additional losses		90	
	Total district heating consumption	862	862	862
	Total district heating production	973	973	973
Fuel for electricity and district heating for residential and services	Power plants (excl. waste, geothermal and nuclear)	878	-	1076
	Fuel assumed for power plants operating in condensing mode	-	878	
	CHP extraction plants (excl. waste, geothermal, & nuclear)	327	-	202
	Fuel assumed for CHP operating in back pressure mode	-	327	
	Centralised peak boilers (excl. waste)	24	10	65
	Centralised heat-only boilers (excl. waste)		14	14
	Nuclear power plants	1700	1700	1700
	Hydroelectricity	394	394	394
	Intermittent RE: wind, solar PV, wave, tidal	1875	1875	1875
Fuel for electricity imbalance	Annual balance of electricity (CEEP)	31	0	101
	Pumped hydroelectric energy storage (PHES) losses	-	-	2
	Additional fuel for power plants due to CEEP & PHES losses	-	-	132
	Extra fuel for power plants in EnergyPLAN compared the reference			129
Final energy consumption (excluding electricity and district heating)	Fuel refinery losses and energy industry own use[a]	[a]	166	3226
	Industry	1208	3068	
	Onsite and offsite CHP and boilers for industrial heat	1796		
	Agriculture/fishing (excluding oil)	64		
	Residential	790	1069	1069
	Services	278		
	Transport	2679	2679	2678
	Jet Fuel	404	404	404
	Petrol	249	249	249
	Diesel	545	562	562
	Agricultural oil consumption	17		
	Gas	0	0	
	LPG	4	4	4
	Electricity	664	664	664
	Biofuels	795	795	795
Total fuel (excluding fuel for non-energy use)	Coal	516	516	519
	Oil	1378	1378	1378
	Gas	2416	2425	2535
	Biomass/waste	5491	*2995*[b]	*3001*
	Renewables		2682	2682
	Nuclear	1700	1700	1700
	Total	**11,501**	**11,696**	**11,816**
CO_2 (Mt)	Energy system	728	728	728
	Assuming CO_2 captured by CCS	377	298	323[c]

[a] Based on the difference between final energy consumption and gross inland consumption minus fuel for non-energy use in the EU-EE projections.

[b] Assuming that biofuels are counted in the primary energy supply and not the biomass required when creating those biofuels.

[c] The differences in the total carbon dioxide emissions have been compensated for by assuming less carbon dioxide is captured by CCS plants. This does not affect the results since the same amount of carbon dioxide is captured by CCS in all scenarios.

2.4 Integrating heat and power sectors

In 2050, the EU-EE scenario in the Energy Roadmap 2050 report projects a total installed electricity generation capacity of approximately 1.5 TW in Europe (Connolly et al., 2013). Roughly two thirds of this capacity is provided by renewable technologies and resources (e.g. hydro-, solar-, wind-, biomass-, and geothermal power), and intermittent sources such as wind power (29% at 432 GW) and solar power (15% at 224 GW) together account for 44% (656 GW) of the total installed capacity. From a power systems perspective, such considerable shares of fluctuating intermittent electricity generation will require increased balancing capacities to maintain grid stability, which can be accomplished by using storage possibilities within the power systems (e.g. hydropower dams, batteries in electric vehicles, large compressed air storages etc.), or by other possibilities available outside the system boundaries of the power sector.

One such external possibility, as principally outlined in Fig. 9, is available through district heating systems utilising power-to-heat technologies in the form of large-scale heat pumps, electric boilers, and thermal storages, in which surplus electricity may be efficiently converted to usable heat. Hereby, a higher integration between heat and power sectors is achieved, including both heat-to-power (cogeneration) and power-to-heat exchanges between the two sectors, which eventually results in higher energy system flexibility and the ability to assimilate more renewable electricity generation. In appended Paper IV, the 2050 HRE-EE scenario elaborates fully on the benefits of this additional energy system flexibility and utilises approximately 5% more wind power than the EU-EE scenario in the final modelling. However, very little is known today about power-to-heat solutions and plausible energy system implications from large-scale deployment of these solutions, given some principal and technology specific studies (Lund and Münster, 2003; Ommen et al., 2014; Zeghici et al., 2014) and some national specific assessments (Böttger et al., 2014; Sowa et al., 2014). Consequently, it is relevant to include into the context of this thesis the assembly of unique Swedish experiences, gained from some 35 years of using large-scale heat pumps and electric boilers in district heating systems, documented in appended Paper V.

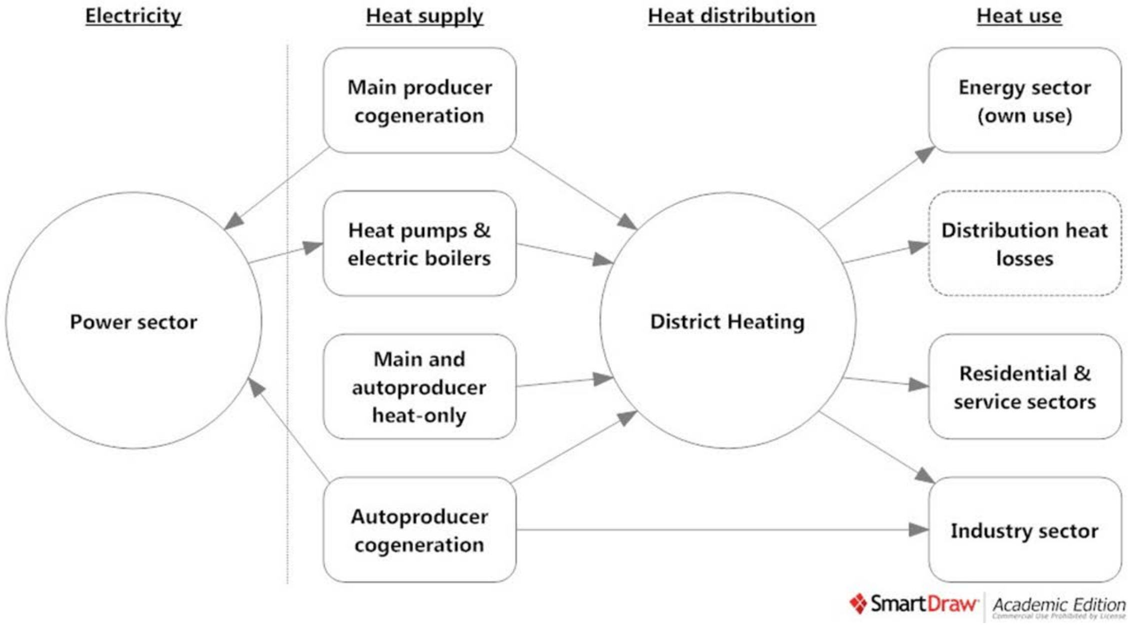

Fig. 9. Principal flow-chart overview of heat supply options for district heating systems, interfaces to power sector, and heat distribution to heat use sectors, as discussed in appended Paper V.

In appended Paper V, electricity surpluses are characterised and divided into different time scales from short-term (hours or days) to more long-term (one to many years), as well as into seasonal and structural surplus conditions. In the case of Sweden, a structural and long-term electricity surplus was created in the 1980s when many new nuclear power plants were commissioned, which resulted in a situation where the ordinary electricity consumers could not absorb the supply surplus. Since the electricity surplus could not be exported to other countries, due to limited export capacity at the time, four domestic activities[24] were initiated to provide sufficient electricity demand to balance production and consumption. The introduction of large electric boilers and large-scale compressor heat pumps in district heating systems was one of these activities. As is elaborated further in the appended paper, these Swedish experiences may prove increasingly valuable as the proportion of intermittent power supply technologies increases in the future European power supply mix. However, the expected electricity surplus in future Europe, which has been foreseen and discussed inter alia in (Lund, 2005) for Denmark, in (Birkner et al., 2013; Modern Power Systems, 2013) for Germany, and in (Minin, 2012) for Russia., will typically be associated with short-term electricity surpluses (as opposed to the long-term and structural surplus situation in Sweden), which implies new operational challenges for the investigated technologies. Appended Paper V addresses briefly some conceivable implications of power-to-heat solutions in relation to electricity surplus characteristics, considers the dependency of low-cost electricity for cost-effective utilisation, and discusses in general the role of district heating systems in highly integrated energy systems.

2.5 Spatial mapping

In the mapping part of the Heat Roadmap Europe project, three fundamental categories of information relevant for district heating expansions are subject for spatial mapping and geographical analysis: excess heat activities and local renewable heat resources, residential and service sector heat demands, and current district heating systems. In appended Paper VI, however, which was published post the two initial project pre-studies (Connolly et al., 2013; Connolly et al., 2012b) and appended Paper IV, local renewable heat resources are excluded from the assessments[25]. Hereby, the three main pillars of information that provides basic data for this study includes excess heat from energy and industry sector activities, building heat demands in residential and service sectors (as briefly already described in section 2.3 Energy system modelling), and cities with district heating currently in operation. The graphical presentation in Fig. 10 illustrates these three separate information flows, along with their associated data sources, methodological steps, concepts, and results. Accumulated per NUTS3 region, total excess heat availabilities and total building heat demands allow quantification of regional heat balances, where after comparative analysis of numerical and spatial data facilitates identification of strategic heat synergy regions, i.e. primary target regions for large-scale implementation of district heating in Europe based on current conditions.

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[24] The four activities were: (i) Introduction of electric heating resistors in domestic oil boilers. (ii) To substitute oil boilers in single-family houses, a general promotion of small-scale electric boilers and heat pumps. (iii) Introduction of large electric boilers for industrial heat demands. (iv) Introduction of large electric boilers and large-scale heat pumps in district heating systems.

[25] During the time that passed between these publications, the used NUTS3 region classification was changed from the 2006 to the 2010 version (including some 80 reshaped regions mainly in Germany, Finland, the Netherlands, and United Kingdom). The reference year for carbon dioxide emission data was furthermore updated from 2009 to 2010 values, as was also the case for main energy statistics sources used (from 2008 to 2010 values). The reason for excluding local renewable heat resources was essentially that further work was considered needed before these heat assets could be included in detailed regional estimates. The idea is to perform a complementary study in the coming years, given that the opportunity arises, focusing explicitly on local renewable heat resources.

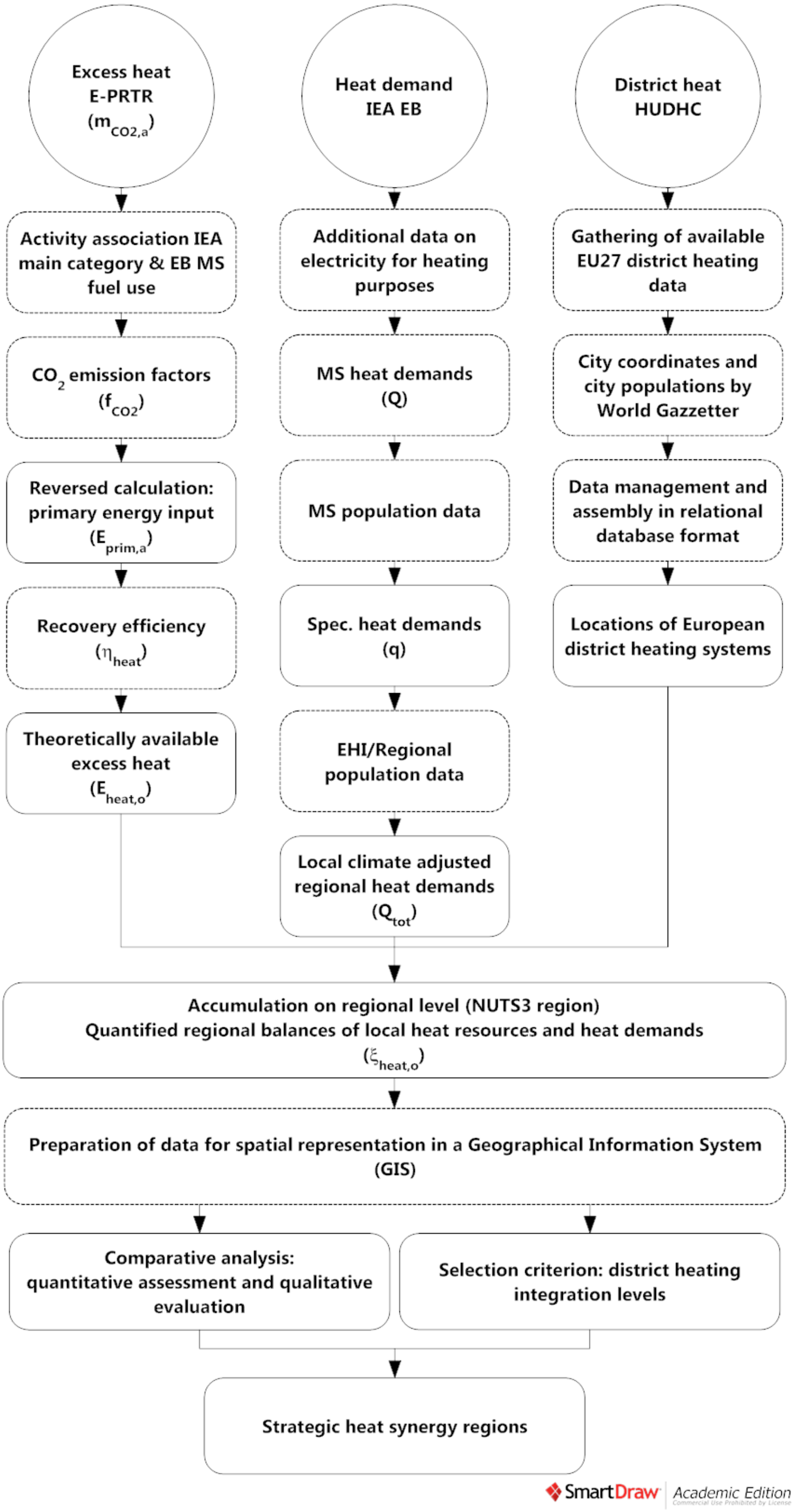

Fig. 10. Principal flow-chart overview of study methodology and data used in appended Paper VI to assess NUTS3 region excess heat volumes (left pillar), regional heat demands (centre pillar), locations of district heating systems (right pillar), and final analytical steps to quantify regional heat balances and identify strategic heat synergy regions.

The geographical distribution of building heat demand concentrations, excess heat generating activities, and district heating systems, share a general spatial coherence in Europe today since all three are associated with human activities mainly in towns, cities, and urban areas. Still, spatial data explicitly determining the locations for these information categories are seldom as readily available as numerical data, or statistics, indicating their quantities. In terms of quantitative data on annually rejected excess heat from energy and industry sector facilities especially, unlike information on their fuel use and geographical locations (described for example in (Kjärstad and Johnsson, 2007)), there are simply no comprehensive sources of information currently available (principal descriptions of excess heat from different industrial processes and fuel combustion activities may however be found, see e.g. (EC, 1982; IEA, 2007; Swithenbank et al., 2013)). For this end, the establishment of annual excess heat volumes in this study utilises an alternative methodological approach, partly inspired by Jönsson and Berntsson (2012), by which these volumes are assessed based on (public) carbon dioxide emission data[26]. Hence, by using volumetric data on annual carbon dioxide emissions from fuel combustion activities ($m_{CO2,a}$) and characteristic carbon dioxide emission factors reflecting average national fuel mixes per main activity sector (f_{CO2}), assessments of annual primary energy input volumes to excess heat activities ($E_{prim,a}$), can be established by the following reversed calculation sequence. First, the annual primary energy input to any given activity is given by:

$$E_{prim,a} = \frac{m_{CO2,a}}{f_{CO2}} \qquad [\mathrm{J/a}] \qquad (10)$$

To reflect fuel use in Member State main activity sectors, the establishment of characteristic carbon dioxide emission factors was arranged by associating standard carbon dioxide emission factors (sf_{CO2}), from stationary combustion (IPCC, 2006), see Table 4, to corresponding fuel types and annual fuel volumes reported per Member State in (IEA, 2012a)[27]. Hereby, depending on carbon intensity and national distributions of fuels used for combustion in energy and energy-intensive industrial sector facilities, differentiated and sector-specific carbon dioxide emission factors per country were made available (see Table 2 in appended Paper VI for a detailed list of factor values).

Table 4. Standard carbon dioxide emission factors from stationary combustion, by fuel type. Source: (IPCC, 2006)

Fuel type	sf_{CO2} [g,CO_2/MJ]
Coal and coal products	94.6
Peat	106.0
Crude, NGL and feedstock	73.3
Oil products	74.1
Natural gas	56.1
Biofuels	101.2[a]

[a] Average value of standard carbon dioxide emission factors for fuel categories "Municipal wastes (non-biomass fraction)": 91.7, "Municipal wastes (biomass fraction)": 100.0, and "Wood - wood wastes": 112.0.

Second, based on calculated annual primary energy input volumes to single facilities (or activities within single facilities), calculated according to eq. 10, corresponding annual

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[26] This data was retrieved from the European Pollutant Release and Transfer Register (v4.2) made available by the European Environment Agency in Copenhagen. No source reference is given in the text here since this data source, as well as most other publicly open data sources used in this work, is given special attention in section 3.1 Public data.

[27] In this assessment, fuel input to thermal power generation in both power-only and cogeneration facilities were compiled with respect to main activity (MA) and autoproducer (AP) facilities. For Waste-to-Energy facilities, an independent data assembly was performed since annual capacity data from 410 EU27 WTE facilities instead was gathered from several complementary sources.

volumes of rejected and theoretically recoverable excess heat ($E_{heat,o}$), are assessed by relating default recovery efficiencies (η_{heat}) to derived input volumes, according to:

$$E_{heat,o} = E_{prim,a} \cdot \eta_{heat} \qquad [J/a] \qquad (11)$$

As presented in Table 5, default recovery efficiency values are set principally to reflect the maximal European excess heat recovery potential from considered activities at current conditions. Hence, excess heat is recognised here as all rejected heat in thermal power generation not absorbed as electricity, and rejected heat in industrial processes not added or maintained in industrial products conceived available for recovery. Given another study objective, these levels could of course be altered accordingly. Third, finally, to complete the reversed calculation sequence, the allocation of default recovery efficiencies (as well as characteristic carbon dioxide emission factors) to corresponding site facilities was facilitated and arranged by assigning, to each of these facilities, a main activity sector category label in accordance with those used in the energy balances of the International Energy Agency (IEA, 2012a).

Table 5. Main activity sector category labels and corresponding default recovery efficiencies. Recovery levels set to reflect maximal excess heat recovery potentials from considered main activity sectors (appended Paper VI)

Main activity sector category	Abbreviation	η_{heat}
Thermal Power – Main Activity	TP-MA	50%
Thermal Power – Auto-producer	TP-AP	60%
Thermal Power – Waste-to-Energy	TP-WTE	60%
Fuel supply and refineries[a]	FSR	50%
Chemical and petrochemical[b]	CPC	25%
Iron and steel[c]	IS	25%
Non-ferrous metals	N-FM	25%
Non-metallic minerals[d]	N-MM	25%
Paper, pulp and printing	PPP	25%
Food and beverage[e]	FB	10%

[a] Not including NACE main economic activities: Extraction of crude petroleum, Extraction of natural gas.
[b] Not including NACE main economic activities: Extraction of salt, Growing of citrus fruits.
[c] Not including NACE main economic activities: Mining of iron ores, Other mining and quarrying n.e.c.
[d] Not including Annex I activities: Opencast mining and quarrying, Underground mining and related operations, and NACE main economic activity; Quarrying of ornamental and building stone, limestone, gypsum, chalk and slate.
[e] Including NACE main economic activities; Manufacture of oil and fats, Manufacture of starches and starch products, Manufacture of sugar, and Manufacture of other organic basic chemicals.

For the quantification of regional heat balances, a ratio was formulated in alignment with the heat utilisation rate (see eq. 8). In allegory, the excess heat ratio ($\xi_{heat,o}$), is defined as the quota of theoretically available excess heat volumes per NUTS3 region (annual sum from all regional excess heat activities) relative local climate adjusted regional heat demands in each corresponding NUTS3 region, according to:

$$\xi_{heat,o} = \frac{\sum E_{heat,o}}{Q_{tot}} \qquad [\%] \qquad (12)$$

An excess heat ratio value of one would then be assigned any NUTS3 region with annual excess heat volumes equalling total heat demands for final consumption of space heating and hot water preparation, and, consequently, no ratio value would occur in the absence of regional excess heat activities. Local climate adjusted regional heat demands in each corresponding NUTS3 region, were calculated as described above in section 2.3 Energy system modelling, which corresponds to the centre pillar sequences rendered in Fig. 10. For district heating systems, the Halmstad University District Heating and Cooling Database was used. See section 3.3 European district heating systems for a separate account of this database.

In the next step, after having quantified regional heat balances on the basis of accumulated building heat demands in residential and service sectors and theoretically available excess heat volumes from energy and industry sectors, all data was prepared for geographical representation in a geographical information system (GIS). For this end, the geo-referenced study data was assembled in a structured query language (SQL) database interconnected to a desktop version of the ArcMap 10.1 GIS interface (ESRI, 2014), whereby spatial analysis was facilitated. Similar approaches to assess regional potentials for excess heat recovery by use of GIS tools has previously been performed by e.g. Clausen (2005) for the Bavaria region in Germany, and by McKenna and Norman to assess UK excess heat recovery potentials from industrial heat loads (2010). Excess heat recovery in district heating systems have also been richly investigated among others by (Fors, 2003; Gebremedhin and Moshfegh, 2004; Holmgren and Gebremedhin, 2004; SDHA, 2002), and found able to use multiple heat supplies cost-effectively (Eriksson et al., 2007; Holmgren, 2006). As for spatial analysis of building heat demands, some studies have used stand-alone GIS to assess geographical distribution on national levels (Möller, 2008; Möller and Nielsen, 2014), or done so in combination with complementary approaches such as laser photogrammetry (AGFW, 2010b), or remote sensing techniques (Sen, 2004). In terms of district heating potentials, Geiß et al. used GIS together with remote sensing techniques to characterize settlement structures (2011), and sustainable district energy solutions in single cities have been mapped and modelled by Finney et al. (2012). Full-scale national and continental studies have also been performed inter alia by (Dyrelund and Lund, 2010; Gils, 2012; Gils et al., 2013; Möller and Lund, 2010; Rattner and Garimella, 2011).

In the last step to identify strategic heat synergy regions, a selection criterion was introduced by which to distinguish suitable Member State candidates for final analysis. According to classification categories used in the Ecoheat4EU project (EHP, 2011) and data referring to (IEA, 2012a), each Member State was sorted into one of five categories reflecting current integration levels of district heating on respective national heat markets, see Table 6. By this division, Member States with very high heat market shares at current (Consolidation), and Member States with negligible shares as well as low motivation for future developments due to generally warm climates (Out-of-scope), were omitted. Hence, 16 Member States in categories Expansion, New Development, and Refurbishment, containing 1075 NUTS3 regions, were selected for final analysis.

Table 6. Selection criterion: Five general categories reflecting current integration levels of district heating (DH) on EU27 Member State national heat markets (appended Paper VI). Sources: (EHP, 2011; IEA, 2012a)

Category	Member States	NUTS3 regions [n]	DH integration level	Final analysis
Consolidation	DK, EE, FI, LT, LV, SE	72	Very high	Omitted
Expansion	AT, DE, FR, IT, SI	665	Medium	Included
New Development	BE, IE, LU, NL, UK	232	Low or medium	Included
Refurbishment	BG, CZ, HU, PL, RO, SK	178	Medium or high	Included
Out-of-scope	CY, EL, ES, MT, PT	134	No or low	Omitted

In this final analysis, performed separately for each selected Member State, the identification process was based on comparative analysis of numerical and geographical data arranged in three steps. The first step consisted of a quantitative assessment, i.e. data analysis, of total heat demands and excess heat volumes per NUTS3 region. For this end, the excess heat ratios of all 834 NUTS3 regions with a ratio value above zero were projected in scatter plots (as in Fig. 11 at left). Given the main objective to identify regions with high heat demand concentrations as well as large excess heat availabilities, the analytical focus was to target regions in the upper right scatter plot segment, as illustrated at centre in Fig. 11.

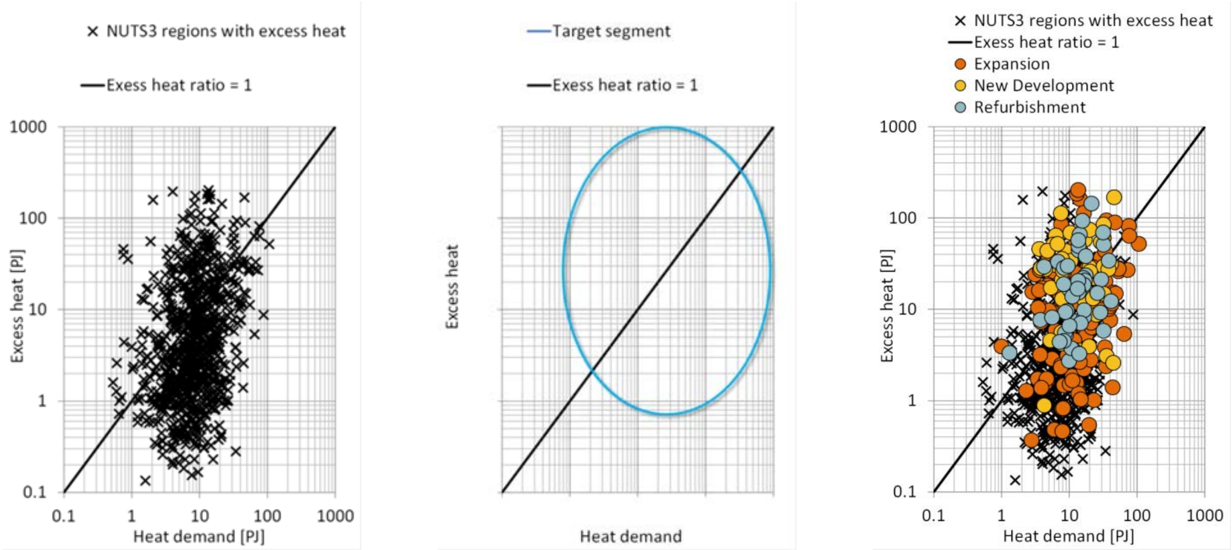

Fig. 11. Analysis of EU27 Member State NUTS3 region excess heat ratios in appended Paper VI: characteristics for 834 NUTS3 regions with excess heat ratio value > 0 (left), target scatter plot segment (centre), and distribution of 206 NUTS3 regions in strategic heat synergy regions (right).

As a complement to the quantitative scatter plot analysis of excess heat ratios, current integration levels of district heating systems in each considered NUTS3 region were as well part of the evaluation. By utilising the Halmstad University District Heating and Cooling Database, indications (total count of systems, annual heat sales, and trench lengths) of cities and regions with district heating systems in operation today, were made available to provide additional information by which to perform the comparative analysis. Last, but not least, the third and final step consisted of a comprehensive spatial analysis (qualitative evaluation) of distribution, concentration, and correlation, between heat demand centres (cities), excess heat locations (facilities), and district heating systems, per NUTS3 region (and neighbouring NUTS3 regions), which allowed the identification of primary target regions for large-scale implementation of district heating. In all, this final selection resulted in 206 identified NUTS3 regions, together constituting 63 strategic heat synergy regions, of which a majority satisfied the main objective (see Fig. 11 at right)[28].

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[28] In appended Paper VI, continental scale European maps can be found for the 2655 considered excess heat facilities (Fig. 2), for the accumulated building heat demands per NUTS3 region (Fig. 4), and for NUTS3 region excess heat ratios (Fig. 7). The 63 identified strategic heat synergy regions are depicted in Fig. 9.

3 Data

As introductory mentioned, the work in this thesis builds partly on the idea to create new theoretical concepts by which to link non-energy related (public) data parameters to energy-specific statistical parameters, whereby new analytical possibilities and perspectives are gained. This section aims to further emphasise the importance of those visionary decisions made in the past – to make environmental data transparent and publicly available – and briefly provide some indications and examples of how this work has benefited from the rich availability of open data today. It should be mentioned, however, that the casual distinction made in this thesis between "data" and "statistics" not entirely correspond to conventional definitions. In the International Encyclopaedia of the Social Sciences (IESS, 2008), the concept of "data" is defined by four different interpretations (epistemic, informational, computational, and fundamental), where essentially only an epistemic and informational understanding resembles how "data" is interpreted here. By these two definitions, data may be regarded as collections of fact and empirical information, in contrast to "statistics" which essentially represent inferences and conclusions drawn from such collections of data (IESS, 1968). It needs also to be mentioned and recognised that, as our world is now entering into a completely new setting in terms of data gathering, storage, and distribution (also known as "big data"), the general availability of data is enhancing rapidly, especially so with respect to spatial data and its many popular applications. In relation to energy systems and technology research, this development may also transform traditional practices of retrieving energy statistics in fixed information packages (CD's, Internet downloads etc.). As more gauging and data gathering systems interact directly with the World Wide Web, continuously updated information should facilitate more swift access to operational information, which eventually should improve relevance and detail of data used to produce research findings.

A characteristic common for all research utilising data and statistics gathered annually, is the fact that updates continuously need to be fed into the analytical models used. In the District Heating and Cooling Research Group at Halmstad University[29], the intentional response to this challenge has been to build model tools appropriately to allow easy integration of annual updates. As in most fields of human activity, time is of essence and many useful work hours have been saved by e.g. always trying to keep input data and statistics separate from the algorithms, calculations, and additional factors used in yielding the results. By this work discipline, less time need to be spent to extract e.g. time series, and any configurations of analytical parameters are easily facilitated since all of these regularly are assembled in one place. Still, gathering, management, and refinement of data and statistics constitute a main share of the time included and the work performed in the appended papers. The software tools mainly used for data storage and management has been the Microsoft Office applications Excel and Access. Some additional data management has also been performed in the ESRI ArcGIS environment. Since algorithms and tools to perform calculations and queries are integrated and available in all of these three applications, most data analyses have also been performed in these programs. The only exception is the energy system analysis performed in appended Paper IV, where the EnergyPlan Energy System Analysis Model was used. The majority of data and statistics used is numerical, i.e. quantitative information, although sometimes acquired and processed from qualitative sources and converted into tabular form.

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[29] The Halmstad University District Heating and Cooling Research Group is a relatively new (2008) and small team led by Professor Sven Werner (district heating and cooling research in general, heat and cold markets, future developments, and education). As of June 2014, the team consisted of Dr. Mei Gong (exergy analyst), and PhD fellows Henrik Gadd (heat loads and metering), Urban Persson (modelling and mapping), and Helge Averfalk (power-to-heat solutions).

3.1 Public data

To give some examples then, several public data sources, and several others not mentioned in the following, are used either directly in the appended papers or was used as references during the work process. As can be seen in Table 7, which presents a list of most significant public data sources related to this thesis, mainly numerical and spatial data are provided by the sources considered (spatial data is of course numerical as well, but the distinction is made here merely to indicate by what interface the data generally is perceived). The numerical sources are dominated by designated emission data records, of which the site-specific data from European energy and industry sector facilities available in the E-PRTR dataset (a public data sources directly related to the Aarhus Convention) is an integral part of the analyses in appended Papers IV and VI. A detail of Northern Italy, where annual carbon dioxide emissions from energy and industry sector facilities have been converted into annual excess heat availabilities (according to eq. 10 and eq. 11), gives a general idea of the usefulness of this data and a vivid example of linkages obtained between public data and energy statistics, as presented in Fig. 12. As for the map in Fig. 12, and all other maps included in this work, the spatial data gathered from e.g. Eurostat (administrative and statistical units), have been conditional for their coming into being. Initially, the Urban Atlas offered valuable orientation and direction around the many large urban zones in Europe and the Corine 2000 seamless vector database, including a spatial division of the European land area in 44 land use classes, has been useful in many evaluations throughout this work. As indicated above, the GISCO population density by square kilometre grid cells was also the foundation upon which the heat demand densities calculated in appended Paper IV could be generated. Several other spatial data sources were also used for references.

Table 7. Examples of significant publicly available data sources used in the appended papers or as references

Source	Reference	Data type	Related to	Description
Urban Audit	(ES, 2014b)	Numerical	Paper I, II	Demographical data for cities and city districts
Urban Atlas	(EEA, 2014)	Spatial	Paper I, IV, VI	Geographical data for cities and urban zones
ArcGIS	(ESRI, 2014)	Spatial	Paper IV, VI	Urban topographies and coordinate systems
CITL	(EEA, 2013b)	Numerical	Paper VI	National carbon dioxide emission data
CORINE 2000	(EEA, 2012)	Spatial	Paper IV, VI	Land coverage and land use classes
E-PRTR	(EEA, 2013a)	Numerical	Paper IV, VI	Site-specific carbon dioxide emission data
Eurostat	(ES, 2014a)	Spatial	Paper IV, VI	Administrative units for Europe etc.
GISCO	(GISCO, 2012)	Spatial	Paper IV, VI	Population density by square kilometer grid
UNFCCC	(EEA, 2013c)	Numerical	Paper VI	National carbon dioxide emission data
INSPIRE	(INSPIRE, 2014)	Spatial	Paper VI	Miscellaneous topo-geographic data
Eurographics	(Eurographics, 2014)	Spatial	Paper VI	Miscellaneous topo-geographic data
EIONET	(EIONET, 2014)	Numerical	Reference	International environment reporting
Eurostat	(ES, 2014c)	Spatial	Reference	Miscellaneous

Another key example where a linkage between non-energy related (public) data parameters and energy-specific statistical parameters was achieved involves the distribution capital cost analysis performed in appended Paper I. A crucial element in this modelling, the population density (p), was – at the time (2009) – publicly available on city district level in the Urban Audit dataset provided by Eurostat[30]. Hereby, assessments of city district specific, as opposed to city average, distribution capital cost levels generated in-depth results upon which the study conclusions could be drawn. As for the remaining three new data categories in the reformulation of the traditional expression for linear heat density, specific building spaces (α), specific heat demands (q), and effective widths (w), multiple statistical sources and reports

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[30] It is unfortunate, and somewhat ambiguous, but city district level information has subsequently been made unavailable in the Urban Audit dataset. City districts are still part of the program coverage, but data on this relatively high level of resolution seems to have been reconsidered as confidential and thus denied public access.

were used to establish their corresponding values (see appended Paper I for further details). Some general information on the cities investigated in appended Paper I[31], with corresponding total building heat demands and district heating heat market shares, estimated and anticipated based on this approach, are assembled in Table 8 (see also the city map in Appendix I).

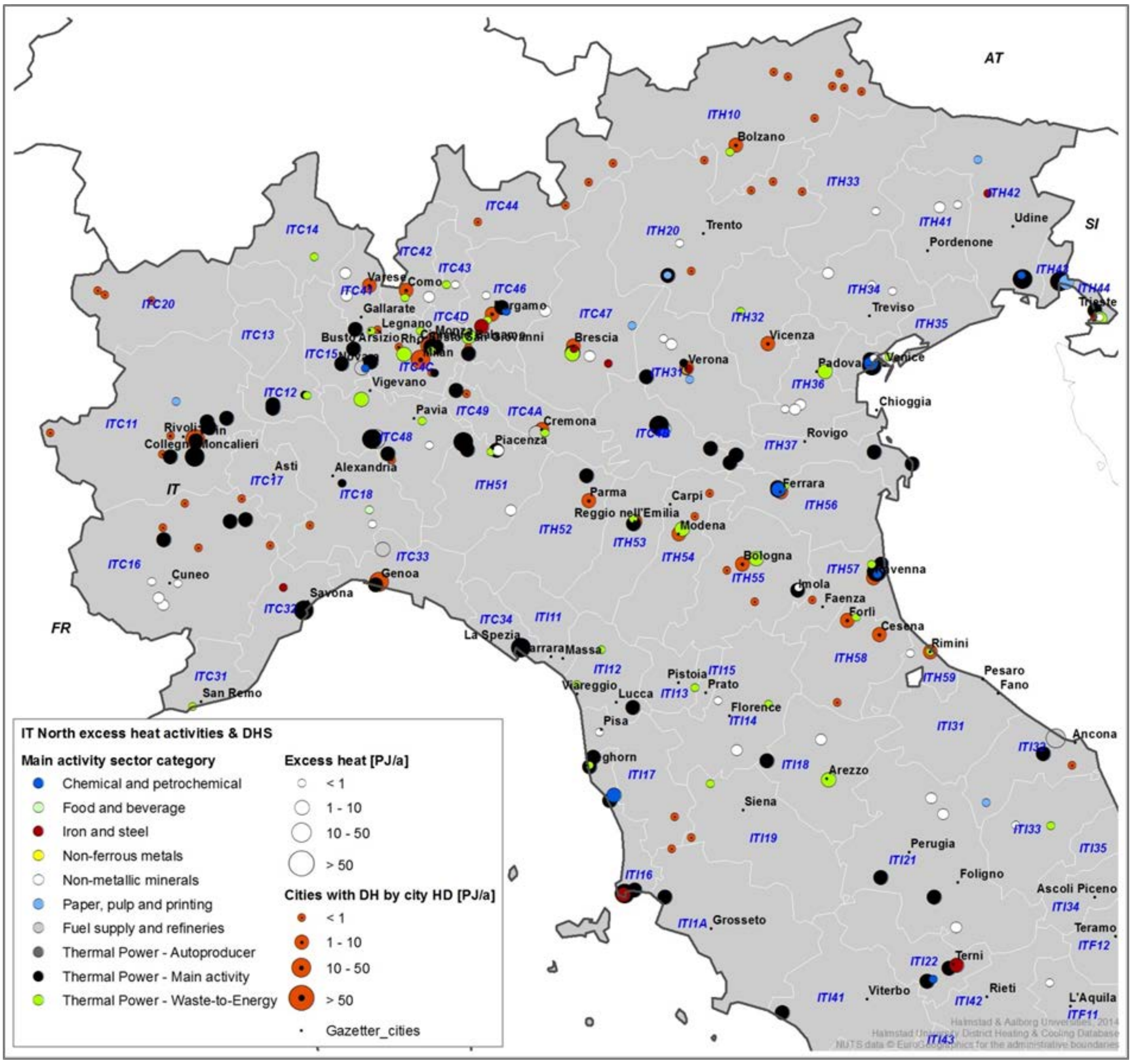

Fig. 12. Excess heat activities, by main activity sector category, and annual excess heat volumes calculated by use of publicly available carbon dioxide emission data from the E-PRTR dataset. Cities with district heating systems currently in operation, stored in the Halmstad University District Heating and Cooling Database, also included (by total city heat demands). Detail of Northern Italy (appended Papers IV and VI).

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[31] Included cities in appended Paper I. In Belgium: Brussels, Antwerp, Gent, and Charleroi. In Germany: Berlin, Hamburg, Munich, Köln, Frankfurt am Main, Essen, Leipzig, Dresden, Dortmund, Düsseldorf, Bremen, Hannover, Nürnberg, Bochum, Wuppertal, Bielefeld, Halle an der Saale, Magdeburg, Wiesbaden, Gottingen, Mulheim a.d.Ruhr, Darmstadt, Trier, Freiburg im Breisgau, Regensburg, Frankfurt (Oder), Weimar, Schwerin, Erfurt, Augsburg, Bonn, Karlsruhe, Mönchengladbach, Mainz, Kiel, Saarbrücken, Potsdam, and Koblenz. In France: Paris, Lyon, Toulouse, Strasbourg, Bordeaux, Nantes, Lille, Montpellier, Saint-Etienne, Le Havre, Rennes, Amiens, Rouen, Nancy, Metz, Reims, Orleans, Dijon, Poitiers, Clermont-Ferrand, Caen, Limoges, Besançon, Grenoble, Ajaccio, Saint Denis, Pointe-a-Pitre, Fort-de-France, Cayenne, Marseille, and Nice. In the Netherlands: s' Gravenhage, Amsterdam, Rotterdam, Utrecht, Eindhoven, Tilburg, Groningen, Enschede, Arnhem, and Heerlen.

Table 8. General information on study countries in appended Paper I. Count of study cities, city districts, and total city populations. Current district heat sales, estimated total building heat demands, and anticipated district heating heat market shares

Country	Cities [n]	City districts [n]	P [Mn]	Q_S[a] [PJ/a]	Q_{tot}[b] [PJ/a]	Estimated urban heat market shares for district heating [%]
Belgium	4	84	1.8	0.1	51	0 %
Germany	38	632	17.3	153	523	29 %
France	31	826	13.2	34	307	11 %
Netherlands	10	161	3.0	14	70	21 %
Total	**83**	**1703**	**35.3**	**201**	**951**	**21 %**

[a] Current district heat sales according to (AGFW, 2010a; CE Delft, 2009; Via Seva, 2008).

[b] Total building heat demands as assessed by the distribution capital cost model.

3.2 Energy statistics

The main energy statistical sources used in the four journal articles appended to this thesis (Papers I, III, IV, and VI), are the national and continental level energy balances for OECD and Non-OECD countries published annually by the International Energy Agency (IEA). In this context, as also indicated in Table 9, the 2010 and 2012 volumes (referring to reference years 2008 and 2010 respectively) were used to gather energy statistics on the supply and consumption of fuels, electricity, heat, renewables etc., by the two general energy system strata of primary energy supply and final consumption. The extraction of selected statistics (summary energy balances, extended energy balances, and/or indicators) is facilitated by the associated browser Beyond 20/20, a user-friendly desktop application allowing users to view, export, and save the stored information by five main dimensions (unit, country, flow, time, and product) (Beyond 20/20, 2014). By complementary use of other data and statistical sources, e.g. data on average conversion efficiencies of final consumption technology systems in building and industry sectors, final end use energy volumes (i.e. the third energy balance level) were assessable based on the original energy statistics. One example illustrating the combined use of energy statistics on fuels and heat used for low temperature heating purposes in residential and service sector buildings (IEA), data on electricity used for such heating purposes (Bertoldi and Atanasiu, 2007; Bertoldi et al., 2012), and spatial data on population densities by square kilometre (GISCO, 2012), is the pan-European heat atlas rendered in appended Paper IV. To illustrate this further (see also sub section 2.3 Energy system modelling above), a detail of the Finnish capitol Helsinki and surrounding NUTS3 regions is presented in Fig. 13. Among other statistical sources frequently used in the appended papers, various statistical reports from Eurostat provided information on e.g. waste management in European countries (ES, 2010b, 2012a), annual electricity and heat yields from cogeneration facilities (ES, 2010a), as well as Member States energy supplies and energy use in general. The annual country-by-country surveys of Euroheat & Power (EHP) also provided national statistics used in creating the Halmstad University District Heating and Cooling Database.

Table 9. Examples of significant energy statistical sources used in the appended papers or as references

Source	Reference	Resolution	Related to	Description
Odyssee	(Odyssee-Mure, 2014)	Regional/National	Paper I, II	Energy use and population counts
Eurostat	(ES, 2014c)	Regional/National	Paper I, III, VI	Energy, waste, cogeneration etc.
UN	(UN, 2010)	National/Continental	Paper IV, VI	Population counts, future projections
IEA	(IEA, 2010)	National/Continental	Paper I, III, IV	Energy balances for 2008
IEA	(IEA, 2012a)	National/Continental	Paper VI	Energy balances for 2010
EHP	(EHP, 2013)	National	Paper I, VI	District heating and cooling systems
ISWA	(ISWA, 2012)	Regional/National	Paper IV, VI	Waste-to-Energy plants in Europe
CEWEP	(CEWEP, 2014)	National	Paper IV, VI	Waste-to-Energy plants in Europe.
EIA	(EIA, 2014a)	National/Continental	Reference	Energy, emissions, population etc.
Tabula	(TABULA, 2014)	National	Reference	Building typologies by country
BPIE	(BPIE, 2014)	Regional/National	Reference	Statistics on European Building stock

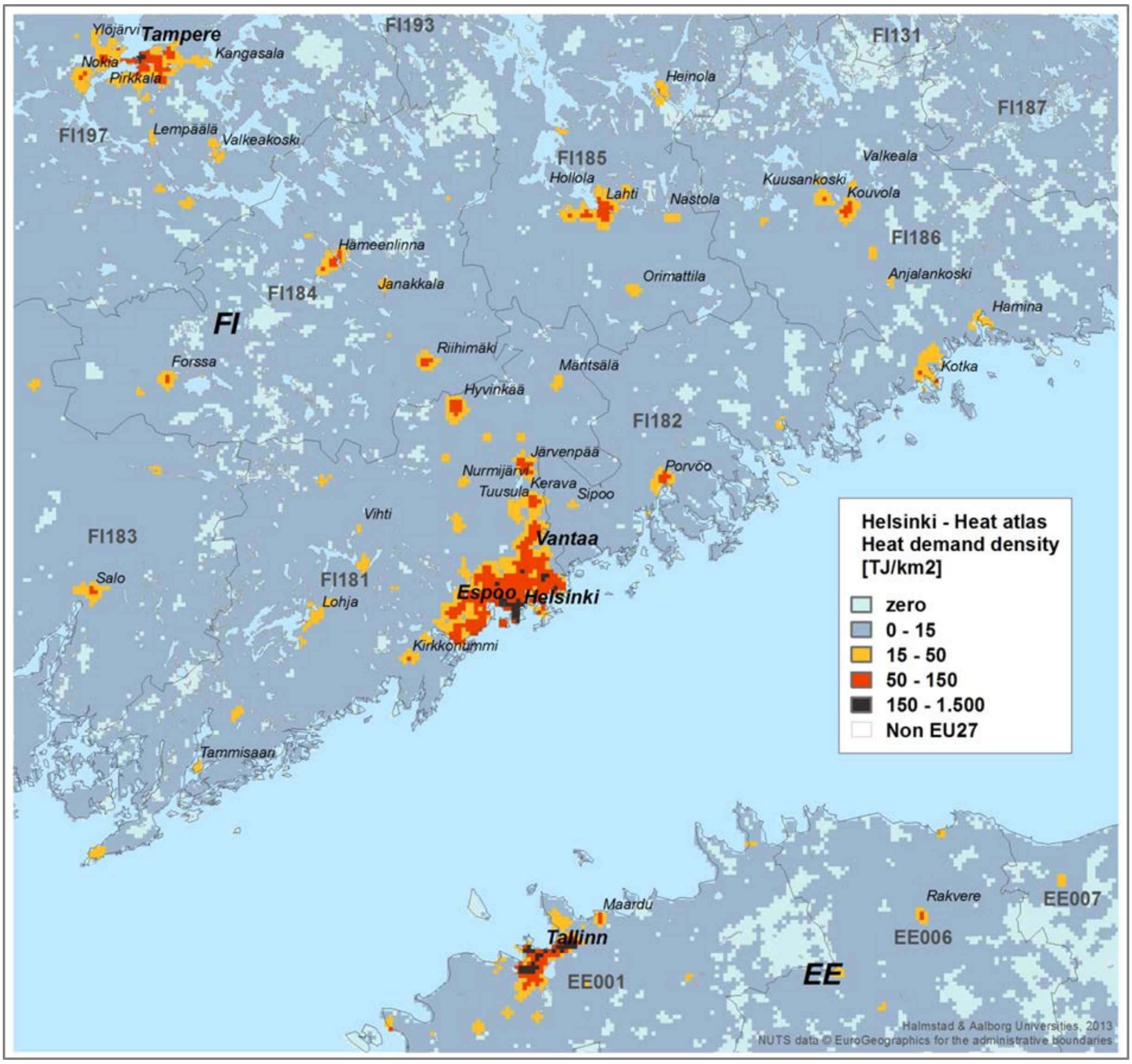

Fig. 13. Heat demand density by four heat demand density classes representing levels of technological development and general feasibility for district heating expansions. Detail of the Finnish capitol Helsinki and surrounding NUTS3 regions (appended Paper IV).

3.3 European district heating systems

In 2009, the District Heating and Cooling Research Group at Halmstad University started to build a dedicated database on district heating and cooling systems currently in operation throughout the European continent. This strenuous endeavour, which in itself was a response to the fact that no coherent data collections on unique European district heating and cooling systems were available at the time[32], was initially performed with the aid of students from the Energy Technology Bachelor and Master programmes given by the School of Business and Engineering at Halmstad University. During the summers of 2009 and 2010, data and

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[32] Apart from data on total heat and cold deliveries at national levels, retrievable in e.g. branch organisation reports and other heat sector publications, dedicated and comprehensive collections of district heating and cooling systems information had been practically non-existent up to this point. Another driver for the initiative was also to counteract the general invisibility of district heating and excess heat recovery in international energy statistics, imposed inter alia by plus 100% energy system efficiencies being forbidden in these, by assembling any available information on European heat and cold distribution infrastructures.

statistics were gathered from a wide variety of available sources, e.g. corporation web pages, energy authority and branch publications on national heat markets, and from personal contacts within the international network of the research group. From the start, gathered data parameters were limited to e.g. city and company names, annual heat sales, and total pipe lengths of identified systems, although numerical information for the latter two (quantitative data) not always have been available. As of November 2014, see Table 10 for current status, the Halmstad University District Heating and Cooling Database (HUDHC, 2014), which was originally stored in an ordinary Excel file format, has been subject to two substantial updates (summers of 2011 and 2012) and converted into an Access relational database format in the last of these revisions. By appropriate query programming, the database includes today automatic functions to facilitate easy updates, search functions, and algorithms to extract current and historical status. For the future, the ambition is further to expand the range of in-data parameter to include information also on heat supply sources used in recorded systems, systems temperature levels of recorded systems, as well as to prepare the database for interactive dissemination by use of the Internet and public GIS server applications.

Another key feature of the HUDHC database is an integrated list of approximately 115,000 geo-referenced European cities (city names, population counts for 2006, and geographical coordinates), by which geographical representations in GIS is made possible[33]. In relation to this thesis, this feature has proven much useful in the analyses performed in appended Papers IV and VI, essentially by being able to map geographical locations of current European district heating systems, and – were possible – having access to quantified annual heat and cold distribution volumes. In appended Paper VI especially, the database constitutes an invaluable complementary source of information in the identification of strategic heat synergy regions. In addition, several other literature sources on district heating and cooling systems have also been consulted in this work, e.g. the technology review in (Rezaie and Rosen, 2012), the developments towards low temperature systems addressed in (Brand and Svendsen, 2013; Christiansen et al., 2012; Dalla Rosa and Christensen, 2011; Lund et al., 2014), and the investigations of heat storages in district heating systems in (Nuytten et al., 2013; Onno, 2011; Sibbitt et al., 2012; Verda and Colella, 2011).

Table 10. Current status (November 2014) of the Halmstad University District Heating and Cooling Database (HUDHC), regarding stored information on district heating (DH) and district cooling (DC) systems, by systems, cities, and countries. Source: (HUDHC, 2014)

Systems	**DH**	**DH EU28**	**DC**	**DC EU28**
Number of systems	4398	3790	109	105
Number of systems with heat data	2404	2081	55	55
Number of systems with length data	1537	1357	5	5
Sum of annually sold heat/cold [PJ]	1009	947	7	7
Sum of pipe trench length [km]	70,779	69,743	86	86
Cities				
Number of cities with systems	3871	3386	107	103
Sum of population in cities with systems [Mn]	165	153	41	41
Number of cities with systems and pop. > 5,000	2531	2284	104	101
Sum of population in cities with systems and pop. > 5,000 [Mn]	162	151	41	41
Number of systems – in cities with population > 5,000	2961	2629	106	103
Countries				
Number of countries with systems	38	26	14	13
Number of NUTS3 regions with systems	733	684	81	79

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[33] See Fig. 5 in appended Paper VI for a continental scale map of all EU27 cities with one or more district heating systems currently in operation, depicted by a scale legend reflecting total building heat demands in corresponding cities. See also Appendix V for a European map illustrating the complete content of the Halmstad University District Heating and Cooling Database as of November 2014.

4 Results

In this section, the main results from the appended papers are presented orderly as attached and as outlined in section 2 Methodology. Hereby, this section starts with sub section 4.1 Feasible expansion potential in urban areas (Paper I and II), and continues with sub section 4.2 Higher energy system efficiency (Paper III), 4.3 Reduced energy system costs (Paper IV), 4.4 Increased energy system flexibility (Paper V), and 4.5 Heat synergy regions (Paper VI). As these sub sector headings indicate, the overarching finding emanating from these studies is the indicia of very favourable conditions for district heating expansions in future European urban areas, a finding initially revealed when analysing the future competitiveness of district heating in appended Paper I. In short, a three-fold, directly feasible, expansion possibility relative to current urban heat market shares found herein not only brought new light upon the cost-effective deployment range of network heat distribution in European cities, it was as well to be decisive for the subsequent studies since it justified further investigations. Consequently, as conceived in appended Paper III, the characterisation of energy system benefits obtainable by increased excess heat recovery from energy and industry sectors arrives at a plausible four-fold excess heat utilisation potential, expressed by the heat utilisation rate and relative to currently best Member State practices. Likewise, modelling of large-scale implementation of district heating in future Europe, as performed in appended Paper IV, suggests equal carbon dioxide emission reductions by 2050 as achieved in the Energy Roadmap 2050 energy efficiency scenario, but at approximately 10% lower total energy system costs compared to this. Additionally, continental charting of geographical locations where these possibilities are most likely to be found, as assessed in appended Paper VI, identifies 63 strategic heat synergy regions in which close to half of the annually rejected excess heat volume in Europe is seized, hereby indicating the locations of primary target regions for such a deployment. Once again, the objective in this context is to focus on key findings relevant for the disposition of the thesis essay and hence not to account for the entirety of generated study results (see result sections in each appended paper for the full detail).

4.1 Feasible expansion potential in urban areas

The primary result indicator chosen in appended Paper I is the combinations of distribution capital costs and corresponding urban heat market shares for the 1703 studied city districts in Belgium, Germany, France, and the Netherlands. These combinations are consecutively sorted from lowest to the highest values and summoned by country average curves to produce the graph properties presented in Fig. 14[34]. As can be seen, the grand total curve levels out to create a relative plateau for urban heat market shares in the interval of 10% to 60% (roughly corresponding to an investment cost interval of 1 to 2 €/GJ respectively), where district heating expansions from current heat market shares can occur with only slight cost increases. Within this interval, apparently, there are remarkably favourable economic conditions for extensions of current district heating systems as well as introduction of completely new heat distribution infrastructures. Keeping in mind that average current urban district heating heat market shares, estimated at 21% for the 83 cities in appended Paper I and at 18% for EU27 (see above, Fig. 3 at right), are far lower than this saturation level (60%). This circumstance suggests a viable, directly feasible, three-fold expansion possibility for district heating systems within these cities, as also detailed in Table 11. Moreover, since the national curves show only minor deviances (all located in the same geographical region) and are homogenous within the identified interval, the results are considered general for all four countries.

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[34] The use of marginal distribution capital costs, as opposed to average distribution capital costs, is motivated by the intention to identify competitive investment cost levels for network extensions in new areas.

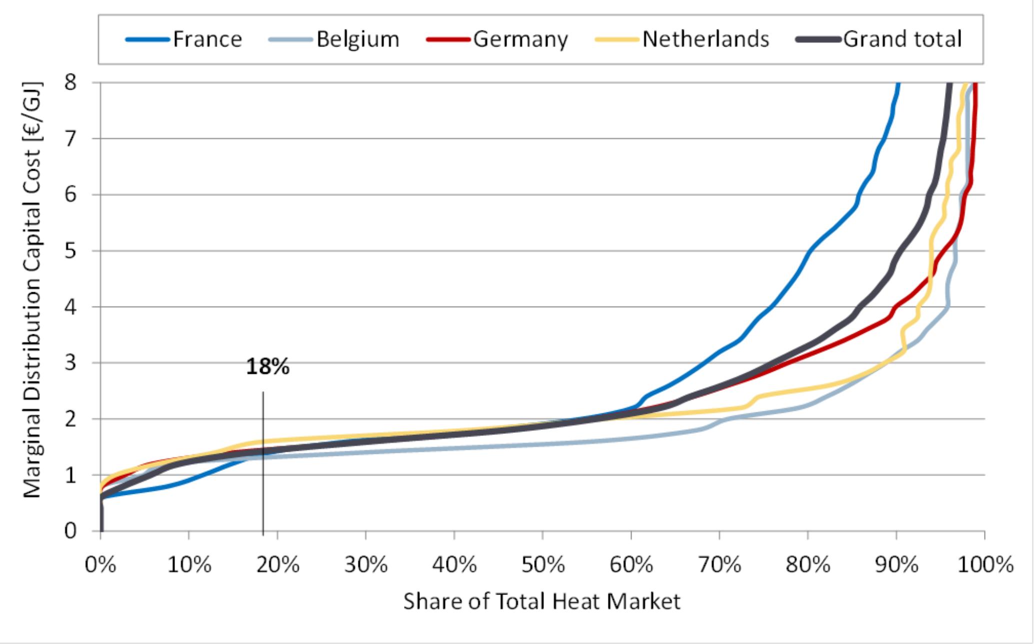

Fig. 14. Current marginal distribution capital cost levels and corresponding urban district heating heat market shares in the four studied countries (BE, DE, FR, and NL) in appended Paper I.

According to these findings, urban district heating heat market shares of 60% should be reachable at marginal distribution capital cost levels at approximately 2.1 €/GJ, an investment cost level essentially equal to that associated to current integration levels of district heating in the studied countries. Hence, urban district heating heat market shares of 60% could be considered an indicative threshold heat market share in European urban areas, where district heating should be directly feasible under current heat market conditions. Based on such an indicative threshold heat market share, 968 study city districts (57%) in appended Paper I, meet the corresponding heat demand density requirements to generate below 2.1 €/GJ distribution capital costs, and 61% (578 PJ/a) of total study building heat demands originate in these, predominantly, inner and outer city areas, as presented in Table 11. Yet, total network investment costs required if to fully realise this expansion possibility represent less than 35% (17.6 G€) of the total anticipated study network investment volume. It is further evident, that as area characteristic shifts from inner city areas to park areas, the cost of investing in heat distribution infrastructures ceases to be economically viable. For 735 low heat demand density city districts, constituting 39% of the total estimated building heat demand, less feasible conditions for district heat deliveries are clearly identified (this heat market segment is visible at above 60% total heat market shares in Fig. 14). District heating systems may still be conceivable in these sparse and less dense areas, but most likely at narrowed margins of operation and investment.

Table 11. Estimated heat demands and required network investments by area characteristics at directly feasible, less feasible, and total conditions for all 1703 studied city districts in appended Paper I

Area characteristics	**Number of city districts**	**Estimated heat demands Q_s [PJ/a]**	**Required network investment I [G€]**
Inner city areas	317	182 (19 %)	4.3
Outer city areas	296	160 (17 %)	5.1
Park areas, feasible	355	236 (25 %)	8.2
Total, directly feasible	**968**	**578 (61 %)**	**17.6**
Park areas, less feasible	735	373 (39 %)	32.9
Total	**1703**	**951 (100 %)**	**50.5**

From the above, it can be concluded that urban district heating heat market shares above 60% should be associated with rapidly increasing marginal distribution capital costs, since this market segment is characterised by low heat demand density areas. Hereby, an indicative threshold plot ratio value of approximately 0.15 to 0.20 can be identified for feasible and cost-effective district heating in the studied cities at current conditions. Given a study average specific heat demand of 0.50 GJ/m^{2}a, this indicative threshold would then correspond to heat demand densities of approximately 75 TJ/km^2 at plot ratios of 0.15, and of 100 TJ/km^2 at plot ratios of 0.20. The impact on these indicative threshold levels of a future development with significantly reduced building heat demands, a consequence of improved energy performance in buildings discussed among others by (Christiansen et al., 2012; Magnusson, 2012; Nielsen and Möller, 2012; Zvingilaite and Balyk, 2014; Åberg, 2014), was evaluated by two alternative scenarios with 20% and 50% reductions of modelled building heat demands respectively. The results from this scenario analysis suggests that reduced building heat demands will imply somewhat higher customer prices for district heat and marginally reduced pay-ability for recovered excess heat into district heating systems, but the general competitiveness of network heat distribution should be principally maintained in city centres and urban areas. In rural and low heat demand density areas, on the other hand, local heating alternatives are expected to dominate.

The core findings from the studies performed in appended Papers I and II, further recognises, generally, that large and compact cities provide most favourable conditions for profitable investments and cost-effective operation of competitive district heating systems. The natural explanation for this are the high population densities characterising compact cities, i.e. the dense concentration of residential and service sector buildings and dwellings accumulating high total heat demand densities, which, in accordance with the principal cost comparison in Fig. 4, satisfies the fundamental requirements for feasible network heat distribution. However, it should be mentioned that the competitiveness and cost-effectiveness of heat distribution infrastructures is evaluated in appended Paper I solely in terms of specific investment cost levels and corresponding heat market shares at these levels. Pure technical aspects of district heat distribution, such as network pipe construction and insulation issues, the performance of sub-stations and valves, as well as operational conditions, are neglected in the analyses. Any expansions of district heating on the studied heat markets, consequently, albeit viable in terms of economic investment, should most likely also have addressed successfully e.g. customer-oriented matters, price model issues, and – most critically – have earned the public confidence and acceptance necessary for any large-scale technology system that essentially are to contribute to higher energy system efficiency in the future.

4.2 Higher energy system efficiency

Supportive of the directly feasible three-fold expansion possibility for cost-effective district heating systems in European urban areas, as established in appended Paper I, the key results of appended Paper III reveal an estimated four-fold excess heat utilisation potential compared to current average levels in EU27. This plausible potential, which refers to excess heat utilisation by means of district heat deliveries to residential and service sector buildings (excluding direct on-site recoveries at industrial facilities), reflects currently best EU27 Member State excess heat utilisation practices from the energy sector (thermal power generation including Waste-to-Energy), the oil refining sector, and five chosen energy intensive industry sectors[35]. In Fig. 15, the 2008 average heat recovery and heat utilisation

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[35] The five energy intensive industry sectors are Iron and steel; Chemical and petrochemical; Non-metallic minerals; Non-ferrous metals; and Paper, pulp and printing.

rates for EU27 and currently best Member State practices provide a clear account of the prevailing improvement range obtainable by expanding European district heating in the future. In Sweden, 71% of total district heat deliveries to residential and service sector buildings (0.154 EJ) consisted of recovered excess heat in this year. Since the total low temperature heat demand in the building sector amounted to 0.258 EJ the same year, a currently best Member State heat utilisation rate of 43% was found in this country. For EU27 on average, a corresponding 75% share of recovered excess heat in total district heat deliveries to residential and service sector buildings (1.34 EJ), relative a total residential and service sector building heat demand of 11.5 EJ, resulted in a modest 9% average heat utilisation rate[36]. Additionally, Member States like Sweden, Denmark, Germany, Belgium, Austria, and the Netherlands, have been most successful in facilitating efficient and environmentally beneficial handling of municipal solid waste streams. Sweden, again, constitutes best Member State practice by reaching a recovery efficiency of 65% from combustible waste fractions (corresponding to a 78% heat recovery rate), well in line with the requirements of the waste directive (EU, 2008).

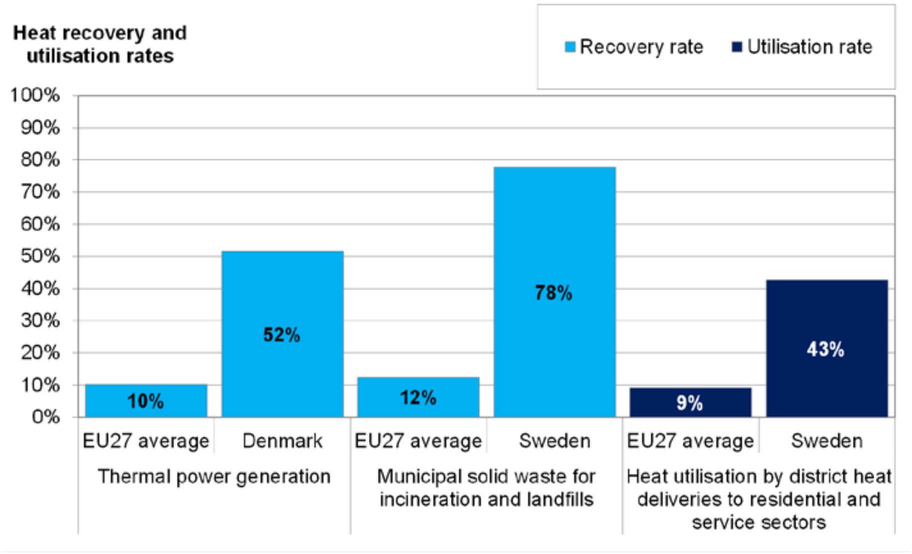

Fig. 15. Average heat recovery rates and heat utilisation rates for EU27 and currently best Member State practice in 2008. Heat recovery rates refer to excess heat from thermal power generation (left) with extracted detail for incineration of municipal solid waste (centre). Heat utilisation rates refer to recovered shares of excess heat from all considered study sectors utilised by district heat deliveries to residential and service sectors (right). Appended Paper III.

In a similar way, if concentrating on a comparison of recovery efficiencies only, hence not considering current excess heat utilisation levels, by applying currently best Member State practices coherently as European average values, the full theoretical excess heat recovery potential is estimated to approximately 10.2 EJ[37] annually, as shown in Table 12. While average EU27 absorption efficiencies in thermal power generation activities are as high as can be expected (37%, see Fig. 4.2 in appended Paper III), total conversion efficiencies suffer significantly from absent or only marginal excess heat recovery from these activities. The

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[36] A complete fulfilment of this plausible potential, given the same shares of cogeneration heat and industrial heat recovery in total district heat deliveries, would correspond to annual district heat deliveries of approximately 5.0 to 6.0 EJ in future Europe. See further Appendix III for a table presenting assessed heat utilisation rates for all EU27 Member states.

[37] It is worth underlining that this theoretical excess heat recovery potential thus represents ~90% of the current total heat demand for space heating and hot water preparation in European buildings.

average EU27 recovery efficiency of excess heat from thermal power generation activities is found at 6% (once again, in 2008), which, compared to the 33% representing currently best Member State practice, found in Denmark, confirms the general situation of excess heat not being recognised as a particularly valuable resource in Europe today. European Waste-to-Energy incineration of municipal solid waste fractions currently not recycled or composted, generates relatively larger shares of recovered excess heat (12%), but, compared to currently best Member State practice these recovery levels are still very low. Industrial heat recovery to district heating systems, finally, is present only in five EU27 Member States (Germany, France, Denmark, Sweden, and Italy), according to national statistical sources (AGFW, 2010a; AIRU, 2009; Energistyrelsen, 2010; SNCU, 2009; Statistics Sweden, 2011), where the 17.5 PJ of recovered industrial excess heat found in Sweden constitute the major part of the contextually insignificant EU27 total at 24.7 PJ.

Table 12. Assessment of the theoretical excess heat recovery potential in EU27 if applying currently best Member State practices as a European average (industrial heat recovery is limited to chosen sub-sectors in study), 2008. (appended Paper III)

	EU27			**Best MS practice**	**Theoretical recovery potential**
Excess heat activity	**E_{prim} [EJ]**	**η_{heat} [%]**	**E_{heat} [EJ]**	**η_{heat} [%]**	**E_{heat} [EJ]**
Thermal power generation	26.3	6	1.60	33	8.68
Waste-to-energy[a]	1.69	12	0.20	65	1.10
Industrial heat recovery	6.24	0.4	0.02	7	0.43
Total	**34.2**	**5**	**1.82**[b]	**30**	**10.2**

[a] Incinerated and land-filled volumes of municipal solid waste.

[b] Reported total main and autoproducer cogeneration heat output in (ES, 2010a), totalling 3.04 EJ in 2008, indicate additional heat recovery being achieved by direct internal heat use at industrial facilities.

The analysis performed in appended Paper III consequently indicates, from an average European perspective, a historical negligence towards the synergetic benefits obtainable by cogeneration of electricity and heat, as well as by improved industrial excess heat recovery and waste management. This poor recognition and utilisation of richly available low temperature excess heat sources may be explained by the vast accessibility and abundance of low priced coal, oil, and other fossil fuels throughout the rise and growth of industrial society, during which the organisation of synergetic supply structures and the idea of optimal resource utilisation essentially was a low priority issue (Holdren, 1990; Schipper et al., 1992). During this era, primary fuels have been supplied and used in e.g. parallel supply structures, where each activity converts energy separately and often with only partial use of the fuel energy content, why a successful transition to serial supply structures represents a fundamental shift in perception regarding our common views on resource value and availability.

The final discussion in appended Paper III analogously suggests that such a transition exceeds purely technical aspects of energy systems technology, implying a new understanding of the organisation of such systems, business models used to finance such systems, collaboration agreements between actors in such systems, and benefit allocation principles within social and industrial institutions involved in such systems. In particular, applying a wide view energy systems perspective in planning processes are of essence since the concept of sequential energy supply interconnect power, heat, industry, and building sector actors at a level of complexity not easily foreseeable by any single actor. A general conclusion is further that such planning should be facilitated not excluding local level perspectives, since the district heating concept is about creating local solutions from local possibilities. All the key methodological approaches and concepts presented in this thesis, the distribution capital cost model (including effective width), the heat rates, the charting of heat demand densities by high spatial resolution, the energy systems modelling, and the spatial mapping of regional heat synergies, should all provide helpful tools to carry out such local assessments.

4.3 Reduced energy system costs

The key results from appended Paper I and III forms a substantiated and supportive basis for proposing large-scale implementation of district heating in future European city areas, both in terms of economic feasibility for network investments and general availability of energy and industry sector excess heat. Hereby, in the energy system modelling performed in appended Paper IV, district heating is expanded to an average EU27 national heat market share of 50% in 2050 (30% in 2030) whereby additional strategic heat resources otherwise not possible to utilise are made available to the European building heat sector. As outlined in Table 13, these main strategic heat sources include excess heat from power plants, Waste-to-Energy incineration plants, industries, as well as renewable heat resources such as geothermal and large-scale solar thermal. The main objective in the GIS mapping performed, to complement the plausible and theoretical excess heat potentials established in appended Paper III by identifying the geographical distribution of these assets and estimating the current potential of utilising these resources in district heating systems, is achieved by spatial analysis of local conditions throughout the European continent. This approach is essential, since, once again, only local conditions disclose the synergies obtainable between local heat assets and heat demands, and it is only at local levels where excess heat from these various activities and resources can be transformed into usable heat by recovery and distribution in district heating systems.

Table 13. Annual district heat (DH) volumes to residential and service sectors in EU27 for the current situation (2010), 2030, and 2050, by strategic heat supply sources, as modelled in the EnergyPLAN energy system analysis and assessed in the GIS mapping of resource potentials. Volumes in [PJ/a]. Appended Paper IV

Main strategic heat sources	Potential[a]	2010 (13% DH)	2030 (30% DH)	2050 (50% DH)
Fossil fuel power generation excess heat and heat from boilers	7075	1120	2410	1540
Waste-to-Energy incineration excess heat	500	50[b]	330	585
Industrial excess heat	2710	25	205	385
Biomass heat	n/a[c]	250	325	810
Geothermal heat	430	7	190	370
Solar thermal heat	1260	0	180	355
Large-scale heat pumps	n/a	0	1290	1875
Total district heating in the modelling	**11,975**	**1460**	**4930**	**5920**

[a] Potential identified in the GIS mapping.

[b] Total heat delivered from waste in 2010 was 170 PJ. However, only 50 PJ/year is assumed to go to residential and service sectors due to the assumptions used to remove industry from the *Energy Roadmap 2050* projections.

[c] The biomass potential was not established in this context, but modelled levels correspond to volumes used in the reference scenario.

As can be seen in Table 13 further, the anticipated HRE-EE scenario in 2050, while considering a total district heat supply of 5.9 EJ by this year, utilises not the full current potential of main strategic heat sources assessed (with the exception of Waste-to-Energy incineration excess heat). This indicates that substantial future reductions of current excess heat availabilities, which are plausible in the event of considerable fuel shifts in energy and industry sectors or due to general economic decline in the coming years, may occur without essentially interfering with the modelled levels of utilisation. In fact, the assessed potential is far larger than conceived utilisation levels. Especially so with respect to excess heat from thermal power generation, industries, and solar thermal heat, although – which is further elaborated in appended Paper VI – the modelled utilisation levels are intended to reflect the recoverable share of the full excess heat potential given its appropriate geographical location in vicinity of urban areas. Additionally, the HRE-EE scenario utilises approximately 5% more wind power than the EU-EE scenario, due to the additional energy system flexibility gained from higher integration between power and heat sectors, which is reflected inter alia by 1.9 EJ (32%) of the total district heating supply originating in heat from large-scale heat pumps.

The final results from the energy system modelling show further, in both the reference and the new heat strategy scenario, that the use of solids and oil for heating purposes are more or less abandoned by 2050, as illustrated in Fig. 16 at left. The final end use building heat demands are reduced to 5.7 EJ for this year in the EU-EE scenario, essentially achieved by individual energy efficiency measures introduced on the demand side of the energy system (end use), and to 9.5 EJ in the HRE-EE scenario (both relative a projected 2015 building heat demand at 14.5 EJ). However, in terms of total costs for the heating and cooling of buildings in residential and service sectors by this year, as presented in Fig. 16 at centre, the HRE-EE scenario avoids the most expensive share of end use energy efficiency investments, relative the EU-EE scenario, which results in approximately 15% lower total heat sector costs. By thus using energy efficiency measures on both the demand side and on the supply side of the energy system, the new heat strategy facilities extended utilisation of excess heat and renewable energy resources for heating purposes, while simultaneously also supporting the integration of more renewable power generation. Hereby, the new heat strategy represents the design of a more cost-effective and resource-efficient energy system solution.

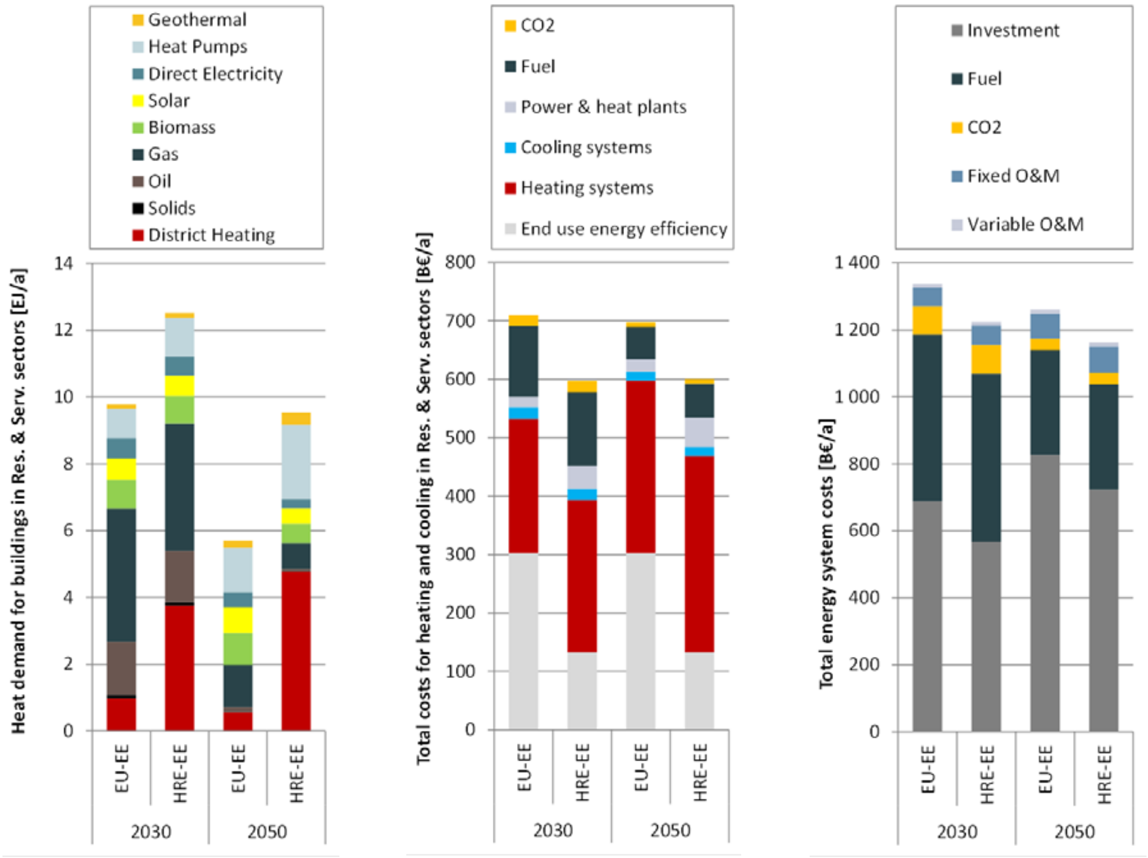

Fig. 16. Comparison of EnergyPLAN output for the EU-EE and the HRE-EE energy efficiency scenarios in 2030 and 2050. Left: total end use heat demands in residential and service sector buildings by supply sources. Centre: total costs for heating and cooling by cost and investment categories. Right: total energy system costs by cost category.

Finally, as indicated at right in Fig. 16, the economic benefits of the new heat strategy also result in lower annual total energy system costs than the EU-EE scenario, while achieving the same level of primary energy supply and carbon dioxide emissions. Both scenarios have very similar fuel, operation and maintenance, and carbon dioxide emission costs, but the HRE-EE scenario reduces the investment costs by approximately 10% (~100 B€/a). From this, one conclusion is that ambitious individual energy efficiency targets should be pursued in Europe, but they should be balanced with targets for structural energy efficiency measures as well.

4.4 Increased energy system flexibility

Among few national European accounts of utilising power-to-heat solutions in district heating systems, the unique Swedish experiences of introducing such solutions to provide additional balancing capacity in the national power system due to a structural long-term electricity surplus is summoned in appended Paper V. During a period of eight to ten years, from the early 1980s to 1990, approximately 1.0 GW of electric capacity in large (>30 MW_e) electric boilers (26 units) and an additional 1.3 GW of heat capacity in 155 large-scale heat pumps (>1 MW_{th}), were installed in district heating systems and industries. As illustrated in Fig. 17, 35% of the total heat supply in Swedish district heating systems originated from these power-to-heat technologies as they peaked in 1990, with decreased use during the subsequent years as electricity demands slowly caught up with supply. The low temperature heat sources used in the large-scale heat pumps this year, sewage water (50%), ambient water (27%), industrial excess heat (15%), and ground water (5%) or air (3%), generated by an average coefficient of performance (COP) of 3.2 an heat supply volume of approximately 26 PJ (18%).

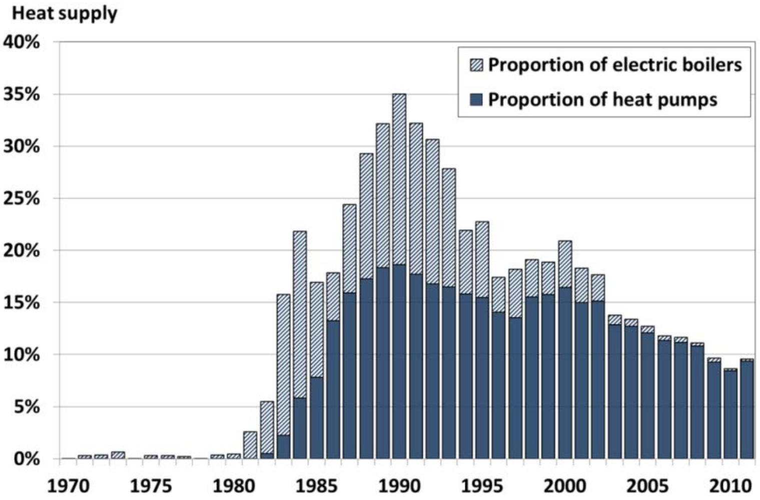

Fig. 17. Annual proportion of heat supplied from electric boilers and large-scale heat pumps into Swedish district heating systems during the years 1970 to 2011. Appended Paper V.

Power-to-heat solutions used in district heating systems may be a cost-efficient measure by which to introduce more flexibility to the energy system, but as they are generally dependent on low electricity prices for viability – the natural consequence of an electricity surplus – they should primarily be used where a recurring electric power surplus occurs. In contrast to the structural long-term surplus situation in Sweden, however, the expected recurring and structural electricity surplus in future Europe, as modelled and anticipated in appended Paper IV, will be characterised rather by intermittent and fluctuating surpluses, which raises concerns as for the operability of these power-to-heat solutions. In the Swedish case, large-scale heat pumps were profitable on the continuous conditions under which they operated, but, due to e.g. increased mechanical wear from repeated start-ups and lower COP at these stop- and start phases, this might not always be the case under short-term surplus conditions. One identified technological research and development challenge emanating from this study is thus the continued development of large-scale compressor heat pumps with improved capabilities to operate discontinuously, despite the shorter maintenance intervals that could be expected under such conditions. Still, proper management within power and heat sectors should allow power-to-heat technologies to contribute to higher flexibility for the future European energy system, especially so in district heating systems equipped with heat storages.

4.5 Heat synergy regions

The GIS mapping of European building heat demands and excess heat availabilities from energy and industry sector activities in appended Paper VI is based on data for 2010, as opposed to the corresponding analysis in appended Paper IV (data reference year 2009), and the excess heat potentials estimated in appended Paper III (2008). For this reason, the results presented in the following deviate slightly from the results and assessed total volumes anticipated in the previous studies. Hereby, the results of this study refer to a total main land EU27 population of 497 million, distributed in 1281 NUTS3 regions, with a total building heat demand of 11.7 EJ, an assessed total primary energy supply to 2655 excess heat activities of 26.1 EJ, of which an anticipated 11.3 EJ is rejected in the form of excess heat. Excess heat activities in thermal power generation (not including nuclear), Waste-to-Energy, and industrial sectors, are found present in 834 NUTS3 regions[38] distributed among all EU27 Member States, and excess heat from thermal power generation dominate the total excess heat volume in general (70%). All Member States, except Malta, have industrial activities generating excess heat from fuel combustion (although at significantly varying degrees), while Waste-to-Energy activities are present in 17 of these countries. The total heat demand for buildings in NUTS3 regions with excess heat activities in operation constitute 81% of the total heat demand, which indicates a generally high spatial correlation between assets and demands, and largest annual volumes of excess heat (as well as largest total population counts) are found in e.g. Germany, United Kingdom, Italy, and Poland.

A total count of 278 NUTS3 regions, located in 25 Member states, have positive regional heat balances, i.e. excess heat ratio values above one, and the total annual excess heat volume in these regions amount to 8.9 EJ (79%), relative a total building heat demand of 2.5 EJ (21%). However, the upper segment of these regions, with ratio values ranging from ~25 to a study maximum at 76.6 (EL133), represents typical regions deselected in the final analysis due to extreme assets at very sparse heat demand density locations. A hands-on average EU27 excess heat ratio of 0.96 is found conceivable and, if only considering heat demands in the 834 NUTS3 regions with excess heat activities currently in operation, the corresponding average ratio value is found at 1.19. In more general terms, these findings translates into the fact that two out of three NUTS3 regions have excess heat generating activities within their boundaries today, and in one third of these, annually rejected excess volumes exceed total building heat demands to generate positive regional heat balances. For EU27 on average, the quota of annually rejected excess heat and building heat demands is more or less an equal balance.

In the final analysis to determine spatially, the locations of primary target regions for large-scale implementation of district heating in future Europe, 206 NUTS3 regions suitable for expansions, new developments, or refurbishments are identified within the 16 Member States selected for final analysis. Altogether, 63 strategic heat synergy regions, consisting either of single or clustered NUTS3 regions, emanated from this charting and, as can be seen in Table 14, 46% (5.2 EJ) of the total EU27 excess heat volume, and 31% (3.6 EJ) of the total building heat demand, is captured within these heat synergy regions. Targeted regions furthermore constitutes no more than 10% of the total EU27 main land area, but are inhabited by 28% of the total study population. Average excess heat activity sector shares in selected regions also differ insignificantly from main study averages, with thermal power generation excess heat dominating at 67%, Waste-to-Energy at 5%, and industrial excess heat at 28%.

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[38] See Fig. 11 at left for the scatter plot distribution of all 834 NUTS3 regions with an excess heat ratio value above zero.

Table 14. NUTS3 regions (N3R) in 16 selected EU27 Member States, all with excess heat ratio (left), identified in strategic heat synergy regions (right). By heat demand (HD), primary energy supply (PES), and excess heat (EH). Excess heat specified by sectors: Thermal power generation (TP), Waste-to-Energy (WTE), and Industrial (Ind). Energy volumes in [PJ/a], reference year 2010. Appended Paper VI

	16 selected MS with excess heat ratio value >0							Strategic heat synergy regions						
MS	N3R	HD	PES	EH	*TP*	*WTE*	*Ind*	N3R	HD	PES	EH	*TP*	*WTE*	*Ind*
AT	20	200	456	167	*63*	*21*	*84*	7	115	357	134	*48*	*20*	*67*
BE	32	311	805	313	*157*	*17*	*138*	8	154	559	224	*110*	*11*	*103*
BG	18	54	382	180	*161*	*0*	*19*	4	21	104	48	*36*	*0*	*12*
CZ	14	267	812	353	*288*	*5*	*61*	5	146	650	279	*222*	*4*	*53*
DE	211	1585	6119	2707	*1980*	*161*	*566*	65	768	3534	1580	*1174*	*85*	*321*
FR	82	1634	1712	645	*236*	*90*	*319*	21	780	1280	509	*222*	*49*	*237*
HU	12	174	306	136	*106*	*3*	*27*	5	108	184	79	*51*	*3*	*24*
IE	7	104	227	102	*88*	*1*	*13*	3	63	96	46	*40*	*1*	*4*
IT	91	1129	2839	1263	*879*	*43*	*341*	18	442	670	297	*212*	*22*	*63*
LU	1	22	35	13	*8*	*1*	*4*	1	22	35	13	*8*	*1*	*4*
NL	27	433	1,348	583	*366*	*46*	*171*	9	182	1020	447	*272*	*32*	*143*
PL	56	724	2171	975	*809*	*0*	*165*	20	290	1185	526	*405*	*0*	*121*
RO	28	217	613	252	*177*	*0*	*75*	10	104	303	120	*68*	*0*	*52*
SI	6	30	81	37	*34*	*0*	*3*	3	19	71	35	*34*	*0*	*1*
SK	7	108	258	90	*41*	*1*	*48*	3	44	217	76	*34*	*1*	*41*
UK	82	944	3229	1477	*1140*	*40*	*297*	24	321	1684	775	*556*	*21*	*198*
Total	**694**	**7937**	**21,392**	**9293**	*6533*	*428*	*2332*	**206**	**3579**	**11,948**	**5187**	*3492*	*250*	*1445*
Shares[a]	**54%**	**68%**	**82%**	**82%**	*70%*	*5%*	*25%*	**16%**	**31%**	**46%**	**46%**	*67%*	*5%*	*28%*

[a] Bold font shares refer to total volumes in Table 7 in appended Paper VI.

The identification process was verified by e.g. projecting all 206 targeted NUTS3 regions as a secondary layer in the excess heat ratio scatter plot of Fig. 11 (see Fig. 11 at right), which confirmed a generally high hit-rate in terms of prioritizing excess heat activity regions with high heat demand concentrations. As such, the study findings once more also confirms the initial potentials that supported the modelled assumptions executed in the HRE-EE scenario (appended Paper IV), where the total district heat supply of 5.9 EJ in 2050 will need to materialise essentially in highly populated and heat demand dense urban areas.

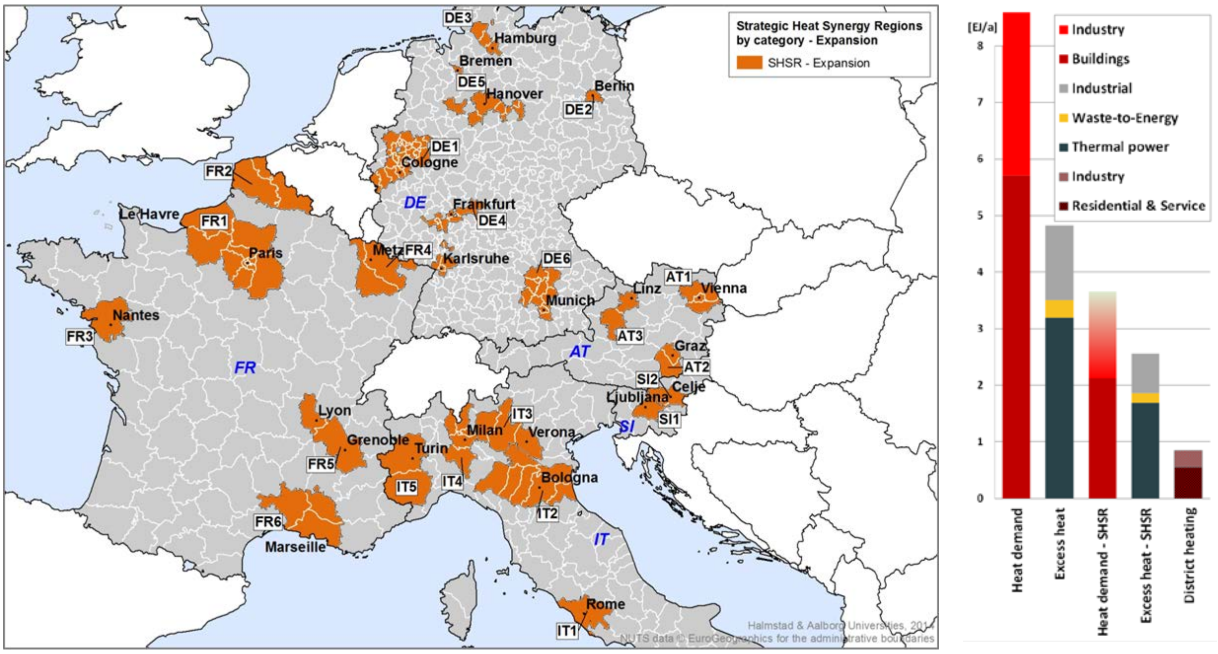

Fig. 18. Category Expansion: 22 strategic heat synergy regions identified in Austria, France, Germany, Italy, and Slovenia (left). At right, heat demands for buildings and industry, excess heat by activity sectors, by Member States and heat synergy region totals. Annual end use volumes of district heat in industry and residential and service sectors. Appended Paper VI.

It is also clear, generally, that the identified heat synergy regions do have strong spatial correlation with the larger urban zones of Europe, urban areas characterised by extensive economic activities, high heat demand concentrations, and beneficial conditions for network heat distribution (see Tables 17 to 19 in Appendix VI for specific results and general information on the identified regions). In Fig. 18, a map of the 22 located strategic heat synergy regions in category Expansion Member States (Austria, France, Germany, Italy, and Slovenia) provides geographical evidence for this general condition. All identified heat synergy regions in this category include NUTS3 regions with district heating systems currently in operation (total annual Member States district heat deliveries in residential and service sectors corresponding to building heat demands of approximately 0.6 EJ), and annual excess heat availabilities (2.6 EJ) exceed total residential and service sector building heat demands herein (2.1 EJ). Since expansions of current district heating systems more easily can absorb new investments, while construction and organisation of completely new heat distribution infrastructures is a more long-term activity, conditions for fast deployment should be widely present in these category Expansion Member States.

In category New Development Member States (Belgium, Ireland, Luxembourg, the Netherlands, and United Kingdom), as presented in Fig. 19, the same spatial characteristics are visible for the 18 identified strategic regions (mainly large urban zones). But, district heating represents here essentially a novel technology to be introduced from low current shares on corresponding national building heat markets (<0.1 EJ), which, in terms of large-scale implementation, implies emphasis on planning and organisational efforts let alone financial and policy support schemes. Yet, also for this category, annual excess heat availabilities in identified heat synergy regions (1.5 EJ) exceed total building heat demands in residential and service sectors (0.7 EJ). The average number of NUTS3 regions per strategic heat synergy region in category New Development is 2.5 (5.2 for category Expansion) and the German Ruhr area (DE1) represents the study maximum with a conglomeration of 27 NUTS3 regions generating a total excess heat volume of approximately 1.0 EJ annually.

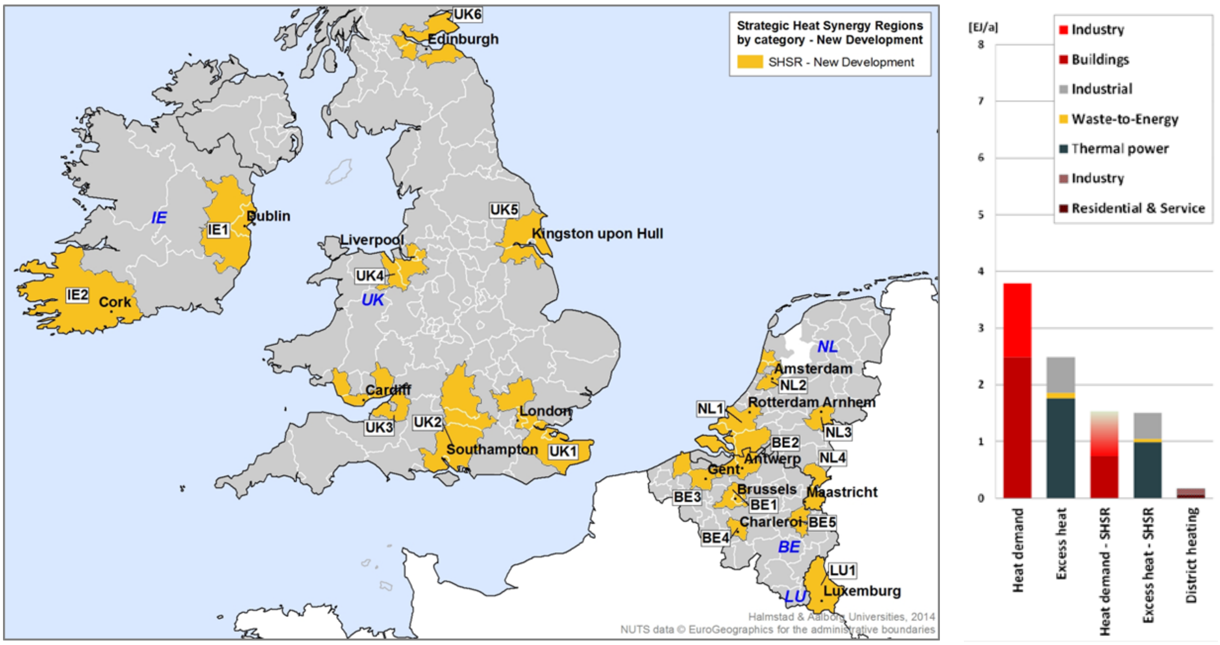

Fig. 19. Category New Development: 18 strategic heat synergy regions identified in Belgium, Ireland, Luxembourg, the Netherlands, and United Kingdom (left). At right, heat demands for buildings and industry, excess heat by activity sectors, by Member States and heat synergy region totals. Annual end use volumes of district heat in industry and residential and service sectors. Appended Paper VI.

In the third category, Refurbishment, 23 strategic heat synergy regions in Bulgaria, the Czech Republic, Hungary, Poland, Romania, and the Slovak Republic, are identified from 178 NUTS3 regions constituting these six Member States, as presented in Fig. 20. On average, heat assets and demands are generally lower in this category compared to categories Expansion and New Development, which partly may be explained by less uniform distribution of energy intensive industrial activities, lower specific heat demands, as well as generally lower access to building energy services. District heating, however, has a long tradition in many of these countries and district heat deliveries to residential and service sector buildings reach urban heat market shares in the order of 35% to 45%, as outlined in Fig. 3 at right. As the category label indicates, the priority for identified heat synergy regions in this category is primarily the upgrading of current systems to reduce distribution heat losses and utilise larger shares of alternative heat supplies, but extends as well to conceivable expansions and new installations. As for the previous categories, anticipated annual excess heat availabilities within targeted regions (1.1 EJ) exceed total building heat demands in residential and service sectors (0.7 EJ), and two NUTS3 regions constitute the average count per strategic heat synergy region (single NUTS3 regions represent 57%).

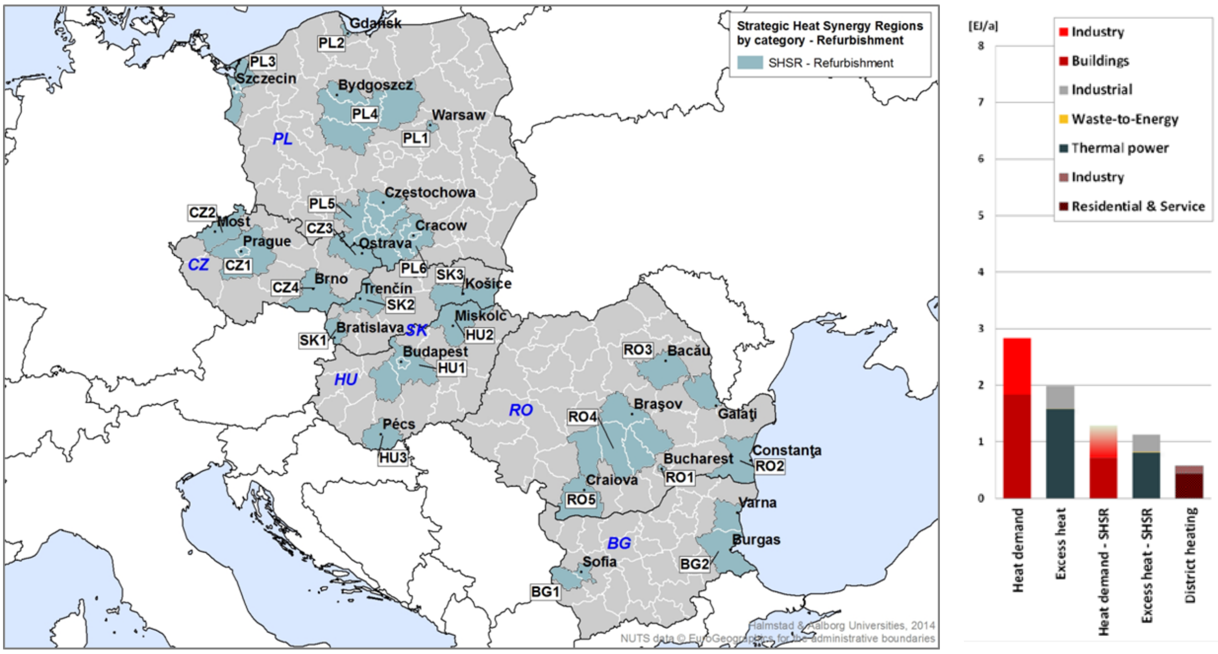

Fig. 20. Category Refurbishment: 23 strategic heat synergy regions identified in Bulgaria, the Czech Republic, Hungary, Poland, Romania, and the Slovak Republic (left). At right, heat demands for buildings and industry, excess heat by activity sectors, by Member States and heat synergy region totals. Annual end use volumes of district heat in industry and residential and service sectors. Appended Paper VI.

When considering these opportunities, however, it should be kept in mind that the results are principal and based on maximal current excess heat recovery potentials from energy and industry sector activities. For reasons further elaborated in section 5 Discussion (and in the discussion section of appended Paper VI), actual realisation levels in targeted regions are likely to be conditioned by a multitude of unique local circumstances (e.g. topographical, thermo-dynamical, geographical, economic, and infrastructural). Since the aim of this study is not to provide detailed local prognoses, but to locate current European heat synergy regions in general, regional in-depth evaluations and sensitivity analyses of local excess heat recovery potentials should follow to determine practicable viability, transmission, and utilisation levels. It is further recognised that opportunities for excess heat recovery exists also in NUTS3 regions and locations not selected and targeted in this analysis.

5 Discussion

According to United Nations projections of the EU28 population growth, the total count by 2050 is estimated at some 520 million (after having peaked at approximately 525 million in 2035) with an urban population share corresponding to 81% in this year (UN, 2010). By this continued and emphasised urbanisation in future Europe, the total urban population increases by a faster rate than the total population (and continues to increase also after the anticipated peak of total population in 2035), why, compared to the current situation, close to 50 million additional European citizens will be city dwellers in 2050. The implications of this development are of course manifold, but should presuppose a continued propagation of the built environment in future Europe, which, from an energy in buildings perspective, should generate rich opportunities for refurbishments of the current building stock and as well new constructions of buildings and infrastructures for the provision of energy services to these buildings. This thesis has demonstrated that district heating and excess heat recovery from energy and industry sector facilities operating inside these urban areas (not to forget the enhanced utilisation possibilities of renewable heat resources available to these), represents a cost and resource efficient alternative to facilitate environmentally beneficial supply structures to provide such energy services. However, it seems appropriate to designate this section to a discussion on contextual challenges and non-technical barriers associated to a realisation of large-scale implementation of district heating, a discussion that hopefully should balance these promising findings and provide indices of additional measures and issues to be addressed and considered during a transition process.

When reflecting upon this favourable and realistic opportunity for Europe to reduce primary energy supplies and annual carbon dioxide emissions, while simultaneously achieving higher security of energy supply, improved local and regional environments, and – which should be underlined – improved industrial competitiveness and new job creation, it would seem relevant to ask why Europe hasn’t already fully exploited this possibility? The answer, regretfully, appears not to be a straight and simple one, and although the energy systemic advantages of district heating and cogeneration have been known for at least a century, the importance of heat has long been routinely underestimated in European Union strategies towards a more sustainable energy system. Instead of recognising district heating and cooling systems as important energy system constituents needed to make use of secondary energy resources (otherwise wasted), heat and cold distribution infrastructures, cogeneration, and waste management, have historically been generally expelled into the shadows of other, more easily conceived, energy technologies and system solutions. And it is perhaps in the added energy system complexity that part of an explanation for this low utilisation of serial supply structures in the European past might be found. As made explicit in the discussion section in appended Paper III, at least three parties need to be involved in a district heating system with excess heat recovery: The owner of the excess heat, the heat distributor, and the heat customers. This sequential structure represents a new (and more intricate) situation in relation to the traditional parallel nature of energy supplies with fossil fuels and/or electricity, and the collaboration and allocation of synergy benefits between these parties, as well as the organisation, operation, and management of serial supply structures in general, represent challenges today neither fully disclosed nor coherently regulated.

A future European energy system characterised by sequential energy supply, by definition thus a more complex and integrated system, hereby implies inter alia redefined business objectives for industries now interacting to a higher degree with dedicated energy utilities. What will be the value of recovered excess heat in such serial supply structures and how will it be determined? Is the heat market itself able to distinguish such cost levels by inherent market competition alone, or will it be necessary to introduce financial and/or policy support measures to obtain overarching objectives? What, in such cases, would be the most appropriate nature of such support mechanisms? Very different legislative frameworks for district heating and cooling are found among European countries today (Werner, 2011) and support measures may range from burden measures (fiscal and carbon taxes), financial support measures (investment grants), market control measures (supervision), and planning mandates (reduced risks). To add to the complexity, anticipated excess heat recycling opportunities may also be limited by on-site thermo-dynamical factors (e.g. excess heat temperature levels, excess heat state of matter etc.), seasonal factors (e.g. annual heat demand variations), and site-specific factors (e.g. unique plant configurations), not to mention the ever present risk of facility closures. Due to the general obscurity characterising future economic developments it is of course difficult to predict such closures, although they should be foreseeable to a certain degree at local levels, but their plausibility implies the necessity for enhanced redundancy in sequential energy supply structures.

The latter aspect raises also a more general issue regarding availability of excess heat in Europe of tomorrow. Albeit beyond the analytical scope of this thesis, it is reasonable to consider briefly, what the future will look like in terms of energy and industry sector activity levels and energy carriers used in these activities. It is plausible, however not expected in contemporary future projections (CEPI, 2014; EU, 2014), that fuel shifts and technology transfers in energy and industry sectors, not to mention an imaginable but improbable general European economic decline, could reduce current volumes of rejected excess heat beyond economically sustainable recovery levels, thus adding ambiguity and risk to short- and mid-term investments in new heat recovery infrastructures. The counter argument (appended Paper VI), would then be that increased recoveries of currently available domestic secondary heat flows, despite their eventual decrease in coming years, would contribute to reduced energy intensities of European energy and industry sector activities, hereby strengthening the general competitiveness of these activities as well as their robustness towards increasing global energy prices. Additionally, if thus considering current excess heat availabilities as merely a transitional source of heat later to disappear, investments in heat distribution infrastructures needed to exploit current opportunities still seem rational, since, once in place, they will have added indispensable flexibility to the energy system. In this respect, district heating and cooling systems should have a significant role to play in the future European energy system, by their inherent capability to increase the utilisation of renewable energy resources as well as to provide balancing solutions in the form of power-to-heat and heat-to-power (cogeneration) solutions to the power sector.

Another key issue that is decisive for the future deployment range of district heating in Europe are the technological, systemic, and organisational level responses to reduced future heat demands in buildings. As has been evaluated in appended Paper I and modelled in appended Paper IV, reduced building heat demands in residential and service sectors impose lower linear heat densities for network heat distribution, which according to eq. 3 corresponds to higher heat distribution capital costs per unit delivered heat. Research and development activities to further facilitate and introduce operational 4th generation district heating systems, i.e. low temperature systems, hereby constitute key efforts for the realisation of the new heat strategy conceived in the latter of these appended papers. The future competitiveness of district heating is then not only a matter of world energy prices, the shape of future cities, and the availability of investment capital, but is essentially so also a predicament of the progress and technological development of heat distribution technologies in themselves. The main targets to be achieved by these research efforts include, apart from operation at lower system temperatures (state-of-the-art: 50 °C by 25 °C), e.g. reduced heat distribution losses, cheaper and more flexible pipe materials, hot water preparation avoiding legionella, trench-less piping etc. In a wider context, this development is parallel to the corresponding development of low energy buildings, i.e. passive houses technologies, and it should be by their mutuality and appropriate interconnectivity that the idea and concept of 4th generation district heating systems will evolve and prosper. As emphasised in this thesis, furthermore, individual energy efficiency measures (low energy buildings, heat pumps etc.) should principally target non-urban areas first, since buildings in these areas will be less costly to refurbish and upgrade, while dedicated urban areas primarily should benefit from structural energy efficiency measures, being most cost and resource efficient in highly heat demand dense locations.

Additionally, in relation to the introductory described world conditions regarding energy use, carbon dioxide emissions, and population trends, it would most probably be naïve to continue believing that we, our world, actually can reduce total primary energy supplies in a near future, considering the continued and escalating growth visible for all three dimensions. But, despite the unforgiving and non-negotiable language of world energy statistics, we do have the possibility to improve the efficiency of the systems we currently have; whereby we could ensure ourselves that our actions are in accordance with, what playfully could be called, sustainable system-ethics and high techno-morals. This would then enable us to say, to our offspring and generations to come, that the energy we use, we at least use as efficiently as we possibly can, and – eventually – this is a realistic and sound ambition. By increased use of structural energy efficiency measures in areas most appropriate for such solutions (e.g. excess heat recovery), and individual energy efficiency measures in corresponding suitable areas (e.g. building refurbishments), the European building heat sector can contribute to absolute reductions of total primary energy supplies in an optimal cost and resource efficient manner. As also indicated above, the main hurdles to overcome for a realisation of these astonishing prospects are essentially not technical, but rather so political, cultural, and informational.

After having been neglected and a forgotten alternative for long, however, it is as if the bells are beginning to toll now, tolling through the city plazas, through the suburbs and towns, the plains, mountains, and valleys of this historical continent. It is as if we have suddenly recalled that the legacy of the righteous warrior is not to have been always victorious, but to have fought well. The pivotal issue, as opposed to relentless arguing about what levels of ambition to be reflected in energy and emission reduction targets, perhaps never to be reached, is the issue of resource efficiency in itself – resource efficiency as a societal virtue! Even in a future energy system based entirely on renewable energy supplies, in which the rationale for efficient energy use from an emissions perspective will be practically cancelled out, it would still be relevant to recover and utilise energy conversion heat losses as efficiently as possible. As such, all energy conversions, also those originating in renewable supplies, require investments, materials, and effort, why the efficient utilisation of available resources in any context should be synonymous with the idea of sustainable energy systems. It should further be noted, that such conversion heat losses may be identified and exploited from many other sources not investigated here (server stations, tunnel ventilation exhausts, sewages etc.).

As a final general remark, this work has been conceived and performed in the genuine belief that research can maintain trustworthiness in society and fulfil its ever so important role of revealing new knowledge and insight to the world community, only by representing an analytical perspective as objective as possibly can be withheld. Hopefully, the methods, approaches, concepts, results, and conclusions presented in this thesis, as well as the context and disposition by which they have been presented here, reflect this principal attitude.

6 Conclusions

The general aim of this thesis has been to investigate to what extent district heating can contribute to a sustainable development and act as a direct counter measure to decrease carbon dioxide emissions from fossil fuel conversions in future Europe. As an initial premise, this investigation starts by assessing feasible and cost-effective expansion levels for network heat distribution on current urban European heat markets, where after characterisation, modelling, and mapping of energy systemic benefits, future energy system costs, and geographical locations of current European heat synergy regions are performed. In the context of the thesis essay, this general aim is transformed into six overall general research questions, each of which reflect the specific and unique issues elaborated in the corresponding appended papers. In the following, briefly but concentrated, the answers found to these general research questions are presented orderly.

First and second, at current conditions and relative current average integration levels of district heating, as assessed in appended Papers I and II, the deployment range for competitive and cost-effective district heating systems represents a three-fold directly feasible expansion possibility for district heat deliveries to residential and service sector buildings in European urban areas. This level of expansion corresponds to 60% urban district heating heat market shares at indicative threshold distribution capital cost levels of approximately 2.1 €/GJ, which in terms of plot ratios correspond to an interval between 0.15–0.20. At specific heat demands of 0.50 GJ/m^{2}a, this interval further translates into anticipated feasibility thresholds for heat demand densities at some 75 TJ/km^2 and 100 TJ/km^2 respectively.

This identified feasibility threshold reversibly also indicates that heat markets shares above 60%, which in terms of area characteristics correspond to more rural and low heat demand density areas, should be dominated by individual heating alternatives such as heat pumps and local boilers. As for the likelihood of reduced future building heat demands, the influence of such a development on the general competitiveness of urban district heating systems is expected to be only marginal, since total urban population shares will continue to increase in the years to come, thus further increasing the population and heat demand densities of European city areas. In the context of the distribution capital cost model, additionally, the demand for district heating pipe lengths in given land areas is determined by the concept of effective width, the only additional information needed to assess linear heat densities once the corresponding heat demand densities has been established.

Third, by comparative analysis of current excess heat recovery and utilisation levels in Europe on average, and relative to currently best Member State practices, as performed in appended Paper III, a four-fold general European excess heat utilisation potential by district heat deliveries to residential and service sectors is found plausible. By expressing the energy systemic benefits obtainable from increased use of district heating in terms of e.g. recovery efficiency, heat recovery rate, and heat utilisation rate, the quantitative evaluation reveal very low current average EU27 excess heat recovery efficiencies in considered activity sectors (5% relative to currently best Member State practise at 30%). In terms of heat utilisation rates, i.e. useful excess heat recoveries distributed in district heating systems, a current EU27 average of 9% is found, which essentially is four times lower than that found for currently best Member state practice (43%). Additionally, from a qualitative perspective, it is recognised in more general terms that a transition from parallel to serial supply structures exceed dedicated technical issues associated to network heat distribution, and involve several circumstantial conditions and challenges to be addressed within e.g. organisational, economic, informational, and political dimensions of society.

Fourth and fifth, as conducted in Paper IV, and aligned with anticipated expansion potentials assessed in the above papers, continental modelling of the EU27 energy system suggests that a combination of structural and individual energy efficiency measures, as opposed to building refurbishments alone, is a more cost-effective approach to reach primary energy and carbon dioxide reduction targets in 2050. By adding district heating to a future European energy system with significantly reduced building heat demands, i.e. using energy efficiency measures on both demand and supply sides of the system, total energy system costs for heating and cooling of buildings will be approximately 10% (~100 B€/a) lower compared to the energy efficiency scenario in the Energy Roadmap 2050 report. By this new and alternative heat strategy, increased recoveries of excess heat from power plants, industries, and Waste-to-Energy incineration facilities are achieved, while as well facilitating higher utilisation levels of renewable energy resources such as wind, solar, and geothermal assets.

To assimilate increased shares of intermittent and fluctuating electricity supplies in this new heat strategy, a higher level of integration between heat and power sectors will presuppose the availability and durability of efficient power-to-heat solutions in district hearing systems. The unique Swedish experiences from using large electric boilers and large-scale compressor heat pumps to absorb long-term structural electricity surpluses, as compiled in appended Paper V, indicate viability and successful operation of such balancing technologies also in future Europe. Applicability under short-term electricity surplus conditions, however, may be partially conditioned by e.g. electricity prices, appropriate system management principles, and the procurement of necessary technical component developments.

Sixth, spatial mapping of the European continent to chart the geographical locations from where a realisation of large-scale implementation of district heating in future Europe should emanate, as performed essentially in appended Paper VI, identifies 63 strategic heat synergy regions that represent primary target regions for most cost-efficient deployment. Correlating principally to large urban zones present in the 16 selected Member States analysed, close to half of current annual excess heat volumes from energy and industry sector activities (5.2 EJ) are captured within these regions. Altogether, these two-hundred and six targeted NUTS3 regions constitute no more than 10% of the total EU27 main land area, are inhabited by 28% of the total European population, and constitute 31 % (3.6 EJ) of the total annual building heat demand in EU27.

As a general conclusion from the answers to these research questions, it is clear that district heating systems should be able to provide cost and resources efficient heat distribution to a major share of urban residential and service sector buildings in future Europe. Since the potential for excess heat recovery and waste management furthermore has remained poorly utilised up to this date, large-scale implementation of district heating should benefit from access to abundant current excess heat availabilities, and, by its utilisation, contribute to improved local and regional environments as well as to higher energy system efficiency in the European energy system. This “step… to address climate change”, additionally, does not pose any considerable technical challenges today, since experiences and knowledge regarding functionality, design, and operability of thermal networks and heat distribution infrastructures has been gained and recorded during a long time of development and use. Quite contrary, the main challenges for Europe to address in order to take this step, and eventually to arrive on this path to improved sustainability, are related rather to non-technical and circumstantial aspects characterising a transition to serial supply structures in general. By the work presented in this thesis, however, it should be clear, beyond any uncertainty, that the towns, cities, and large urban zones of Europe will have lead roles to play in such a transition if the European community decides to follow this path towards decarbonisation.

7 Future research

One important lesson learnt through the course of these doctoral studies is that research essentially is an iterative process. For every problem solved, new questions arise, and it lies within the nature of analytical investigation to reconsider continuously approaches, findings, and previous conceptions. In relation to this work, one such concept is that of effective width, presented and discussed in relation to the distribution capital cost model in appended Papers I and II, were extended studies on the relationship between plot ratios and district heating pipe lengths could refine and sharpen the precision of the power function used in this context. Future work in this respect, could also address a wider range of typical area characteristics and settlement structures, especially so those associated to 4th generation operational conditions as well as those of district cool distribution.

Another field relevant for future research is that of different industrial excess heat generating processes, where a development of principal factors, i.e. industrial process excess heat factors, describing rejected heat volumes per unit primary energy input to unique activities and processes, could simplify future modelling of industrial excess heat potentials based on statistical and operational information. Such a progress could improve the facilitation of detailed calculations and assessments of viable transmission distances between industrial excess heat locations and near-by district heating systems, which eventually would support the identification and arrangement of new serial supply structures. In this respect, the full cogency and impetus of GIS tools, of which merely a fraction has been used here, should come into effect when practically assessing configuration, design, and dimensions of future local excess heat recovery applications and heat synergy projects.

In relation to geographical mapping, additionally, spatial characterisation of heat demand density distributions at below square kilometres resolution, i.e. by hectares, may further enhance proper designation and evaluation of heat demand concentrations plausible for district heat supplies. By such raster grid cell representations, uniform descriptions of building heat demands at very high levels of resolution should prove increasingly valuable for European Member States when, in accordance with the new energy efficiency directive, designing national heating and cooling plans. Since such mapping eventually also will extend to building cool demands, which predominantly are found in service sector buildings and thus not spatially distributed in direct coherence with population densities (as is the general case for the residential sector), the development of appropriate methodological approaches to properly assess the geography of cooling demands represent yet another area for future research.

Other areas suitable for future research may be that of quality improvements and extended coverage range of international energy statistics, where e.g. the development and inclusion of appropriate concepts to make excess heat recovery visible constitute an important field. As for specific energy statistic practices, a future research challenge of its own could be the development of alternative methods by which to more correctly allocate fuel inputs to cogeneration activities. From a policy perspective, the fostering of transparent and sensitive policy frameworks, taking into consideration current integration levels, unique conditions, and varying initial positions in different Member States, should as well be important in the support of new district heating and cooling developments. From an energy systems perspective, finally, future research within the field of energy and environment technology should continue the study of how to interconnect, integrate, and optimally arrange power, gas, and thermal infrastructures in the overarching ambition to determine the design and configuration of genuinely smart energy systems solutions for future Europe.

8 Svensk sammanfattning

Den här avhandlingen presenterar ett antal metoder och tillvägagångssätt som kan användas för att undersöka och fastställa omfattningen med vilken utökad användning av fjärrvärme i framtidens Europa kan bidra till ökad energieffektivitet och minskade koldioxidutsläpp. Det huvudsakliga skälet till att föreslå storskalig utbyggnad av fjärrvärme som en strukturell energieffektiviseringsåtgärd för att uppnå dessa föresatser härrör väsentligen i belägenheten att merparten av Europas byggnader idag alltjämt är beroende av energitillförsel från fossila bränslen för rumsuppvärmning och tappvarmvatten. Samtidigt genereras årligen betydande mängder spillvärme från Europeiska kraftverk och industrier, lågvärdig värmenergi, vilken till skillnad från att som idag huvudsakligen ödslas outnyttjad, på ett realistiskt sätt skulle kunna återvinnas och därmed ersätta avsevärda andelar av nuvarande ineffektiv energitillförsel. En grundläggande förutsättning för genomförbarheten av denna förnuftiga framtidsutsikt är emellertid att infrastruktur nödvändig för återvinning och distribution av spillvärme finns på plats, vilket dessvärre är långt ifrån det generella fallet i dagens Europa.

Av denna anledning följer undersökningen en struktur som börjar med att inledningsvis klargöra huruvida fjärrvärme kan vara ett konkurrenskraftigt alternativ på nuvarande värmemarknader i Europeiska städer, vilket beräknas i en distributionskostnadsmodell, varpå de energisystemmässiga fördelarna med utökad fjärrvärme karaktäriseras och lägger grunden för en uppskattning av plausibel utbyggnadspotential baserat på jämförelseanalys. I nästa steg genomförs modellering av ett framtida Europeiskt energisystem för år 2050, där fjärrvärme expanderats i enlighet med denna potential, för att uppskatta de totala energisystemmässiga kostnadsfördelarna relativt ett alternativt scenario med fokus huvudsakligen på individuella energieffektiviseringsåtgärder. Slutligen kartläggs, med hjälp av ett geografiskt informationssystem, de nyckelområden i nuvarande Europa varifrån en framtida storskalig utbyggnad av fjärrvärme skulle kunna ta sin början.

Resultaten påvisar generellt starkt stöd för ett förverkligande av föresatserna, huvudsakligen så genom att påvisa en trefaldig direkt lönsam utbyggnadspotential för fjärrvärme i nuvarande storstadsområden, men påtalar också nödvändigheten av att adressera ett flertal ytterligare, huvudsakligen icke-tekniska, frågeställningar och utmaningar för att uppnå en framgångsrik omvandling till mer energieffektiva tillförselsstrukturer i framtidens Europa.

9 Acknowledgements

As briefly mentioned in section 1.4 Outline and context, the research and studies presented in this thesis has received funding and financial support from several different sources, all of which hereby are gratefully acknowledged. For the work performed in the first three appended papers, means to do so was provided by the Swedish Energy Agency through the Swedish System Solutions project. For the subsequent Heat Roadmap Europe studies in appended papers IV and VI, financial support was provided in part by Euroheat and Power in Brussels to perform two pre-studies in 2012 and 2013, and, for the main studies, by the Strategic Research Centre for 4th Generation District Heating Technologies and Systems (4DH project) at Aalborg University in Denmark. By being assigned, in 2012, to one of thirteen PhD positions in this project, itself funded partly by the Danish Council for Strategic Research and partly by a consortium of industrial partners and district heating companies, the main funding body for the latter part of these studies were made available (including appended Paper V). Additional funding has also been received through the International Energy Agency Implementing Agreement on District Heating and Cooling (Annex X), from the District Heating within the Energy System project within Fjärrsyn (the Swedish district heating research programme), and as well in the form of internal funding provided by the School of Business and Engineering at Halmstad University in Sweden.

A significant part of the work included in this thesis has also been performed in joint projects between members of the District Heating and Cooling Research Group at Halmstad University and research groups from other universities, both in Sweden and abroad. Main collaborations have been those performed with the Division of Energy Technology at the Department of Energy and Environment at Chalmers University in Gothenburg, Sweden, and those performed with the Department of Development and Planning at Aalborg University in Denmark. Other significant external research collaborators include the Department of Energy and Environmental Management in Developing Countries at Europa-Universität Flensburg, Germany, the Department of Civil Engineering at the Technical University of Denmark, and the Institute for Energy Technology at Dresden University of Technology in Germany. Among these institutions, there are a number of people who have provided support, inspiration, and encouragement to me during the course of these studies, and although I owe to all of them my sincere thankfulness, perhaps not all will be mentioned in the following.

First, I want to express my deep gratitude to Professor Filip Johnsson at Chalmers University of Technology, for accepting me as a PhD student in early 2009, for giving me the opportunity to align with the Alliance for Global Sustainability project Pathways to Sustainable European Energy Systems (parallel to the Swedish System Solutions project), and for guidance along the way. I would also like to take the opportunity to thank all the researchers involved in this project for showing me a first glimpse of how inspiring life as a researcher can be. Special thanks to Eoin Ó Broin, Johanna Mossberg, Johan Rootzén, Daniella Johansson, Érika Mata Las Heras, Jan Kjärstad, and Mikael Odenberger, for stimulating discussions and communications throughout the course of the project. In relation to this project further, heartfelt thanks also to Bo Rydén, Erik Axelsson, John Johnsson, and Thomas Unger at Profu AB in Mölndal, to Anders Sandoff at the School of Business, Economics, and Law as well as to Professor Åsa Boholm at the School of Public Administration & CEFOS, both at the University of Gothenburg. At Chalmers University of Technology additionally, sincere thanks to Professor Jan-Olof Dalenbäck, Ulrika Claeson Colpier, Dumitru Knejer, Inger Hessel, Sandra Malentacchi, and Marie Iwanow for administrative assistance during these studies and in finalising this thesis.

Second, learning to know Professor Henrik Lund at the Department of Development and Planning at Aalborg University in Denmark, along with his dedicated and skilled group of researchers in the field of energy systems analysis and planning, has been nothing but pure pleasure. It is not very easy to express the thankfulness and appreciation I feel for having been taken in to your atmosphere of inclusion and encouragement. The best I can do is: Thank you, Henrik, for being who you are! In direct relation to the appended papers IV and VI, sincere thanks also to David Connolly for your excellent work, your kindness, and humour, and to Professor Bernd Möller at Europa-Universität Flensburg, for your genius and many teachings, without which my progress in spatial analysis would have taken place at a much slower pace. At Aalborg University, further, special thanks also to Professor Brian Vad Mathiesen for your encouragement and support, to Professor Poul Alberg Östergaard, Steffen Nielsen, Kenneth Hansen, and David Drysdale for good cooperation and understanding. Thanks also to Pernille Sylvest Andersen and Mette Reiche Sörensen for your administration and practical support.

Third, at Halmstad University in Sweden, my home turf, at this point, since so many of you has followed me from a close distance during this lengthy and laborious work, I would like to embrace you all, but now that would of course be a little inappropriate. Instead, let me try to express in these few words the sheer gratitude I feel for having the privilege of being one amongst you. A heartfelt thanks to Marie Mattsson, former head of the Division of Natural Sciences at the School of Business and Engineering, for having faith in me, for your kind leadership, and for allocating internal research funds on my behalf. Thanks also to all members of the previous Energy Technology staff group, especially so to Göran Sidén for taking me aboard, to Professor Jonny Hylander for sharpening my edges, to Ingemar Josefsson for your calm and steady steering, to Mei Gong for additional supervision, to Erik Möllerström and Fredric Ottermo for friendly companionship. A special thanks to Helge Averfalk for being the great (traveling) companion you are and for assisting in drawing flow-chart for this thesis, and a big hug to my nearest and dearest PhD student fellow Henrik Gadd, with whom I have been able to share both the burdens and joys of doctoral studies during the last five years. Thank you, Henrik, I am going to miss you! At Halmstad University, special thanks also to Margaretha Borgström and Henrik Florén for your support. Additional thanks to Bengt Hjort, Professor Sigfried Fleischer, Åke Spångberg, Sylvia Waara, Lars-Erik Widal, Ingrid Svetoft, Professor Stefan Weisner, Per-Magnus Ehde, and Marie Magnheden, as well as to Monica Lindström for administrative work and to Henrik Barth, Dean at the School of Business and Engineering. Extended thanks also to Daniel Nilsson for major contributions in building the Halmstad University District Heating and Cooling Database.

Now, many more names could and should be mentioned here to reflect appropriately the extent of the international research community that I have come to be a part of during these fantastic years, but, eventually, the ink is about to run dry. However, before ending, I need to express my sincere thanks for always friendly and constructive discussions with Akram Sandvall and Erik Ahlgren at Chalmers University of Technology, with Professor Svend Svendsen and Hongwei Li at the Technical University of Denmark, and with Robin Wiltshire and Ciro Bevilaqua at the Building Research Establishment in the UK. This has certainly also been the case with Jan Eric Thorsen and Oddgeir Gudmundsson at Danfoss in Denmark, with Birger Lauersen at the Danish District Heating Association, and with Tomislav Puksec and Tomislav Novosel at the University of Zagreb in Croatia. In this respect, special thanks also to Yves Delaby at Dalkia and to Nicolas Février and Aksana Krasatsenka at the DHC+ Technology Platform within Euroheat and Power in Brussels. For invitations to hold lectures, furthermore, special thanks to Professor Leif Gustavsson at the Linnaeus University in Växjö, Sweden, and to Pierre Hollmuller and Jérôme Faessler at the University of Geneva in Switzerland.

So, with the last remaining droplets then, I want to thank the people who have been most influential and conditional for this work to come into existence. Most important of all, thank you Professor Sven Werner at Halmstad University in Sweden, my main supervisor, mentor, and colleague through the full extent of this work, what the cliché says could not be more appropriate in this respect. It is true, this work would never have been possible to conceive nor perform without the inspiration, guidance, continuous and patient teachings, the experience, knowledge, discipline, and speed of mind that you possess. Sincerely, Sven, I thank you from the depth of my heart for sharing this with me and for opening the door!

Finally, I myself would not have been where I am today without the love, understanding, and genuine support that I have received from my parents, Rolf Persson and Agneta Englund, during this as well as in previous phases in my life. I dedicate this work to you… and to you, Selma Alexandra, my beloved daughter, who has come into this world like a streak of lightning, illuminating to a restless searcher the true joy and meaning of life. Thank you! Personal thanks, for being there, also to Anse, Sandra, Zamo, Inger, Stig, Camila, Ronan, Lisa, and Svante.

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11 Appendices

11.1 Appendix I – Map: 83 study cities (Paper I)

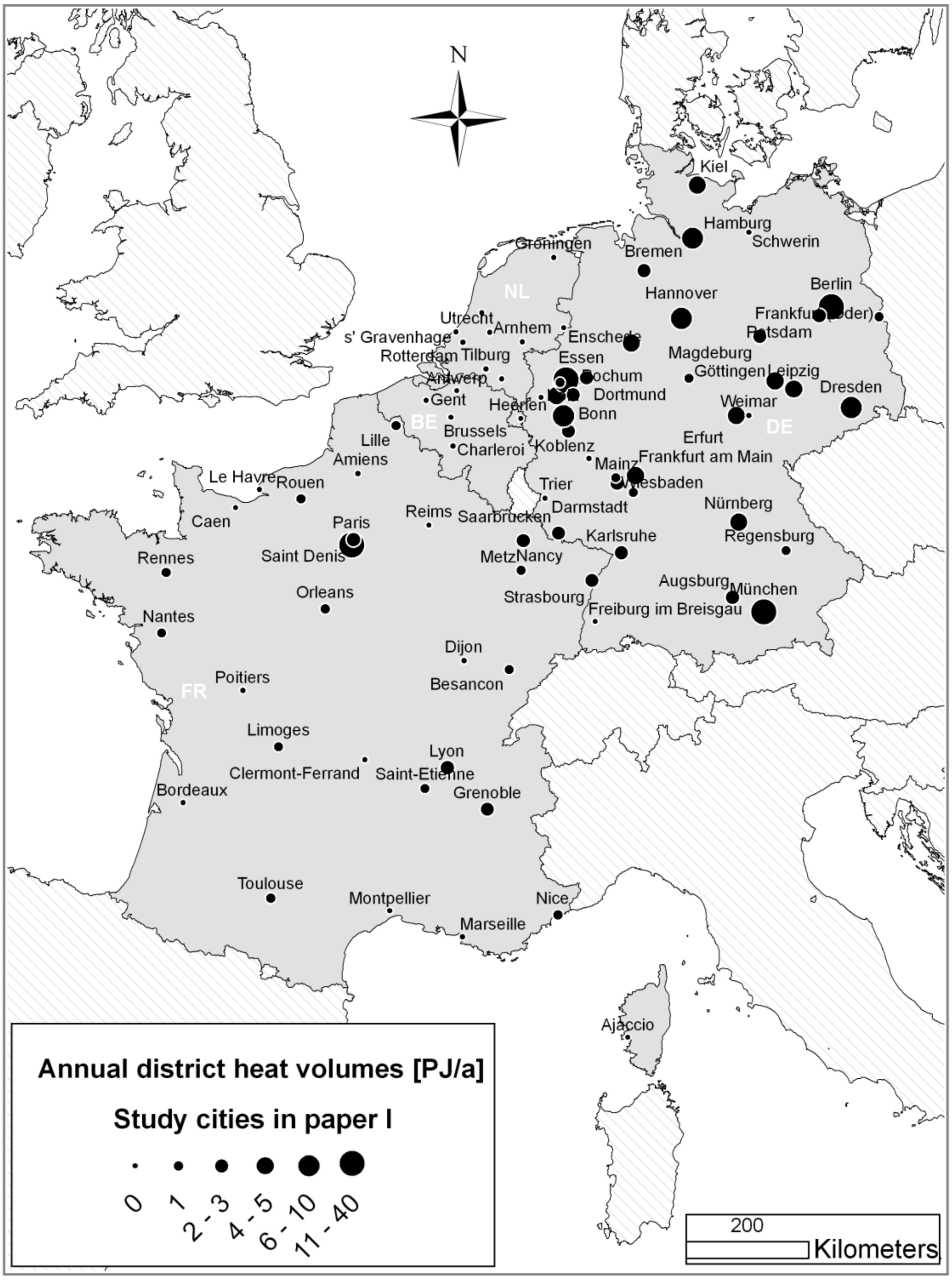

Fig. 21. Annual district heat deliveries in 83 study cities investigated in appended Paper I. Data for the year 2005 (AGFW, 2010a), 2006 (Via Seva, 2008), and 2009 (CE Delft, 2009).

11.2 Appendix II – Table: Urban district heating heat market shares (Paper I)

Table 15. General information on 83 studied central European cities in appended Paper I. Annually sold heat in district heating systems; model estimated residential and service sector heat demands, and urban district heating heat market shares

Member State	City code	City name	Annually sold district heat [PJ]	Model estimated heat demand [PJ]	Urban district heating heat market share [%]
be	be001c	Bruxelles / Brussel	0	27.26	0
be	be002c	Antwerpen	0	12.54	0
be	be003c	Gent	0.12	6.30	2
be	be004c	Charleroi	0	5.20	0
de	de001c	Berlin	39.92	99.79	40
de	de002c	Hamburg	10.16	52.81	19
de	de003c	München	18.00	37.69	48
de	de004c	Köln	6.97	29.18	24
de	de005c	Frankfurt am Main	5.03	18.65	27
de	de006c	Essen	8.57	17.22	50
de	de008c	Leipzig	5.34	13.45	40
de	de009c	Dresden	6.62	12.67	52
de	de010c	Dortmund	1.92	17.26	11
de	de011c	Düsseldorf	3.45	18.28	19
de	de012c	Bremen	2.42	17.51	14
de	de013c	Hannover	6.17	16.78	37
de	de014c	Nürnberg	4.45	14.61	30
de	de015c	Bochum	1.59	11.76	14
de	de016c	Wuppertal	2.09	10.91	19
de	de017c	Bielefeld	3.28	10.30	32
de	de018c	Halle an der Saale	2.99	6.61	45
de	de019c	Magdeburg	1.25	6.24	20
de	de020c	Wiesbaden	0.79	8.81	9
de	de021c	Göttingen	0.34	3.76	9
de	de022c	Mülheim a.d.Ruhr	0.32	5.59	6
de	de025c	Darmstadt	0.37	4.60	8
de	de026c	Trier	0.05	3.35	1
de	de027c	Freiburg im Breisgau	0	6.08	0
de	de028c	Regensburg	0.45	4.17	11
de	de029c	Frankfurt (Oder)	1.00	1.98	50
de	de030c	Weimar	0.26	1.83	14
de	de031c	Schwerin	0	2.78	0
de	de032c	Erfurt	3.90	5.85	67
de	de033c	Augsburg	2.14	7.91	27
de	de034c	Bonn	1.85	9.90	19
de	de035c	Karlsruhe	2.38	9.09	26
de	de036c	Mönchengladbach	0	8.04	0
de	de037c	Mainz	1.27	6.09	21
de	de039c	Kiel	3.73	7.21	52
de	de040c	Saarbrucken	1.54	6.42	24
de	de041c	Potsdam	2.12	3.85	55
de	de042c	Koblenz	0	3.80	0
fr	fr001c	Paris	18.31	47.88	38
fr	fr003c	Lyon	1.20	26.55	5
fr	fr004c	Toulouse	0.50	14.37	3
fr	fr006c	Strasbourg	1.48	10.50	14
fr	fr007c	Bordeaux	0.02	16.07	0
fr	fr008c	Nantes	0.59	13.44	4
fr	fr009c	Lille	0.90	25.46	4
fr	fr010c	Montpellier	0	9.89	0
fr	fr011c	Saint-Etienne	0.33	8.77	4
fr	fr012c	Le Havre	0.20	5.55	4
fr	fr013c	Rennes	0.60	8.83	7
fr	fr014c	Amiens	0.29	3.93	7
fr	fr015c	Rouen	0.57	9.19	6
fr	fr016c	Nancy	0.42	6.38	7

Member State	**City code**	**City name**	**Annually sold district heat [PJ]**	**Model estimated heat demand [PJ]**	**Urban district heating heat market share [%]**
fr	fr017c	Metz	1.36	5.16	26
fr	fr018c	Reims	0.08	5.04	2
fr	fr019c	Orleans	0.76	6.36	12
fr	fr020c	Dijon	0.22	5.70	4
fr	fr021c	Poitiers	0.28	3.11	9
fr	fr022c	Clermont-Ferrand	0.13	6.52	2
fr	fr023c	Caen	0.07	5.07	1
fr	fr024c	Limoges	0.37	4.69	8
fr	fr025c	Besancon	0.56	4.16	14
fr	fr026c	Grenoble	2.81	8.61	33
fr	fr027c	Ajaccio	0	1.44	0
fr	fr028c	Saint Denis	1.23	4.15	30
fr	fr029c	Pointe-a-Pitre	0	1.97	0
fr	fr030c	Fort-de-France	0	3.86	0
fr	fr031c	Cayenne	0	2.15	0
fr	fr203c	Marseille	0	21.60	0
fr	fr205c	Nice	0.68	10.81	6
nl	nl001c	s' Gravenhage	1.30	11.96	11
nl	nl002c	Amsterdam	1.40	17.15	8
nl	nl003c	Rotterdam	4.50	12.52	36
nl	nl004c	Utrecht	4.50	5.73	79
nl	nl005c	Eindhoven	0.30	4.75	6
nl	nl006c	Tilburg	1.30	4.57	28
nl	nl007c	Groningen	0	4.07	0
nl	nl008c	Enschede	0.70	3.51	20
nl	nl009c	Arnhem	0.10	3.25	3
nl	nl010c	Heerlen	0.30	2.22	14
Total			**201.17**	**951.08**	**21**

11.3 Appendix III – Table: EU27 Member State heat utilisation rates (Paper III)

Table 16. Assessment of EU27 Member State heat utilisation rates by district heat deliveries to residential and service sectors in 2008, extended detail of study results from appended Paper III

EU27 Member States	Industrial heat recovery in district heating systems [EJ]	District heat deliveries to residential and service sectors [EJ]	Share of recovered heat in total district heat deliveries [%]	Q_{tot} [EJ]	ξ_{heat} [%]
Sweden	0.0175	0.154	71	0.258	43
Denmark	0.0027	0.090	82	0.183	40
Finland	0	0.097	74	0.196	37
Lithuania	0	0.029	50	0.057	25
Bulgaria	0	0.019	84	0.064	25
Czech Republic	0	0.059	78	0.236	19
Latvia	0	0.022	53	0.060	19
Poland	0	0.200	64	0.709	18
Romania	0	0.060	78	0.293	16
Austria	0	0.053	68	0.247	15
Estonia	0	0.019	29	0.039	14
Slovak Republic	0	0.027	53	0.109	13
Hungary	0	0.033	70	0.220	11
Slovenia	0	0.005	78	0.039	10
EU27	**0.0247**	**1.394**	**75**	**11.502**	**9**
France	0.0012	0.157	98	1.702	9
Germany	0.0003	0.304	74	2.733	8
Luxembourg	0	0.001	100	0.019	7
Netherlands	0	0.033	89	0.503	6
Greece	0	0.002	100	0.162	1
Belgium	0	0.004	100	0.343	1
Italy	0.0001	0.006	100	1.099	1
Portugal	0	0.001	100	0.105	0
United Kingdom	0	0.018	0	1.473	0
Cyprus	0	0	-	0.010	-
Ireland	0	0	-	0.119	-
Malta	0	0	-	0.002	-
Spain	0	0	-	0.520	-

11.4 Appendix IV – Map: The pan-European heat atlas (Paper IV)

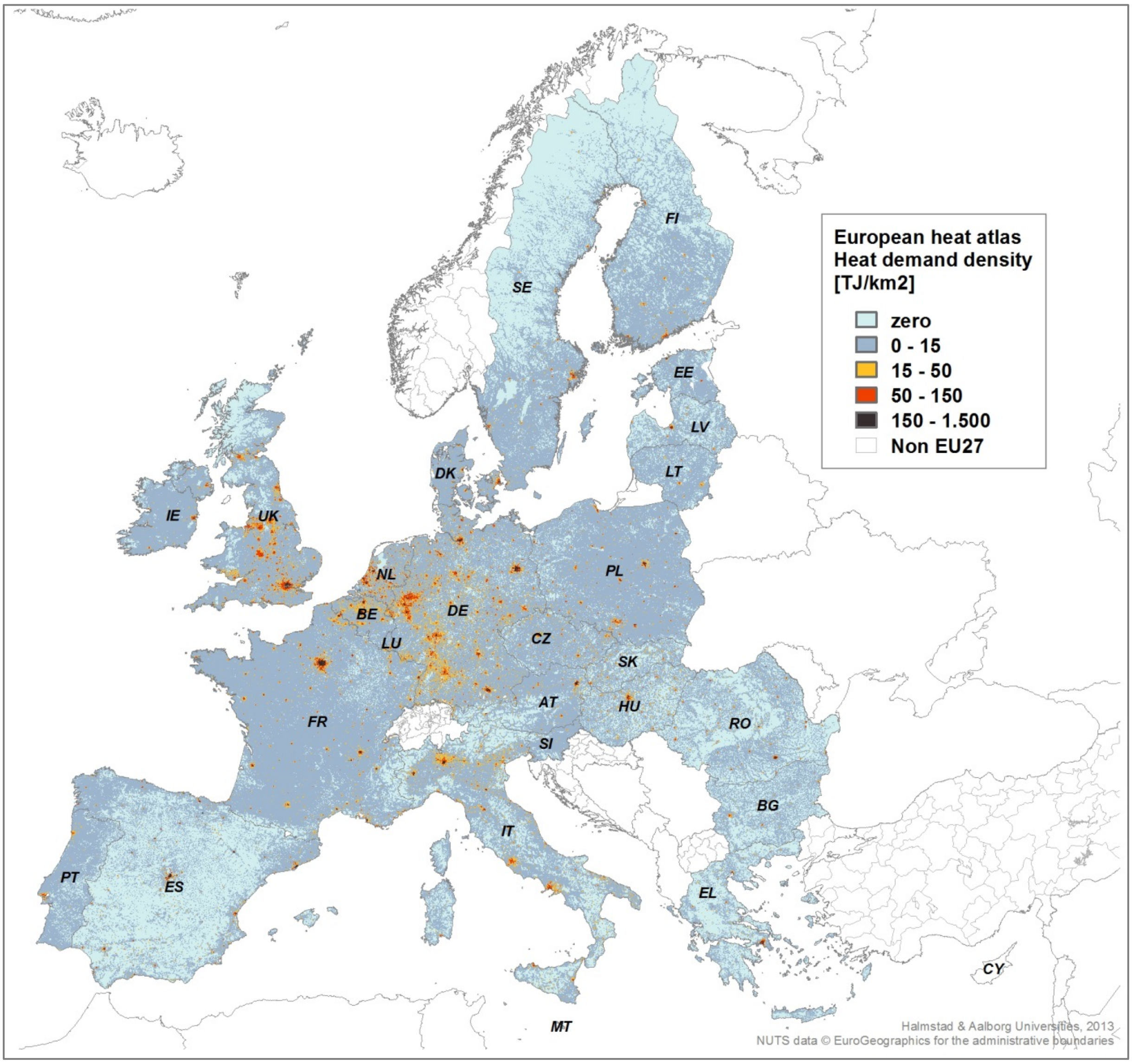

Fig. 22. The pan-European heat atlas by heat demand density classes based on the GEOSTAT 2006 square kilometre population density raster grid and 2008 IEA energy statistics for EU27.

11.5 Appendix V – Map: The HUDHC Database (Paper VI)

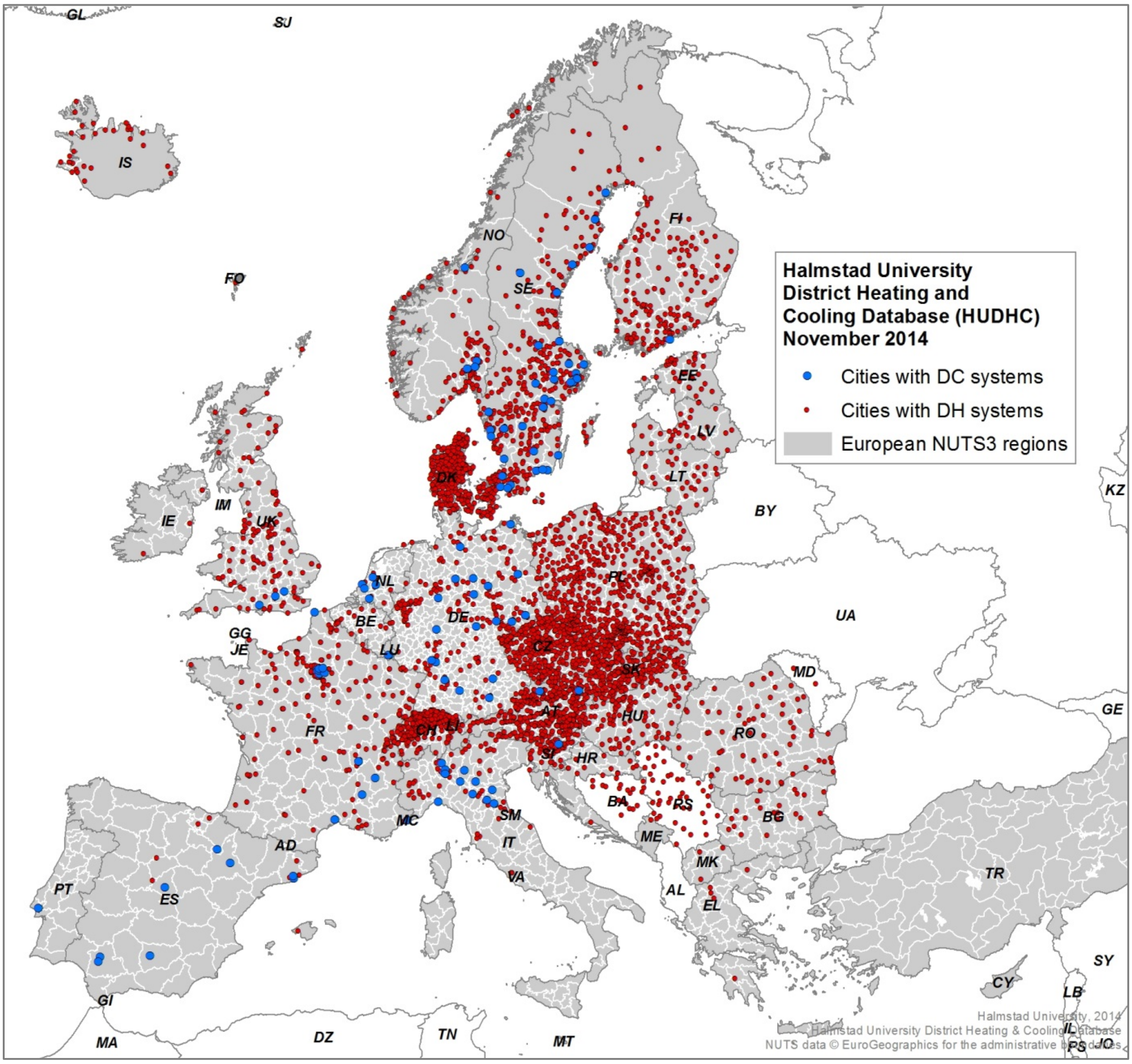

Fig. 23. 3871 European cities with one or more district heating system (4398) and 107 cities with district cooling systems (109) currently in operation, as stored in the Halmstad University District Heating and Cooling Database (November, 2014).

11.6 Appendix VI – Tables: Strategic heat synergy regions (Paper VI)

Table 17. Total annual residential and service sector heat demand in buildings (HD) and total excess heat volumes (EH), specified by activity sectors: Thermal power (TP), Waste-to-Energy (WTE), and Industrial (Ind), for 22 strategic heat synergy regions in category Expansion. Detail of study results from appended Paper VI

Label	**Name**	**HD [PJ/a]**	**EH [PJ/a]**	**TP [PJ/a]**	**WTE [PJ/a]**	**Ind [PJ/a]**
AT1	Vienna	72.4	68.7	32.3	15.8	20.6
AT2	Graz	17.8	13.0	1.0	0.0	12.0
AT3	Linz-Wels	24.8	52.7	14.5	3.7	34.6
DE1	Rühr area	305.5	1037.9	819.9	39.4	178.5
DE2	Berlin Potsdam	106.3	52.0	41.7	10.3	0.0
DE3	Hamburg Bremen	85.1	95.6	52.8	12.5	30.3
DE4	Frankfurt Mannheim Karlsruhe	114.1	179.3	111.5	12.6	55.2
DE5	Hannover	69.2	139.4	101.9	6.5	31.1
DE6	Munich Ingolstadt	88.1	76.3	46.5	3.8	26.0
FR1	Paris & Seine-Maritime	413.2	158.5	53.1	31.0	74.3
FR2	Nord & Pas-de-Calais	118.3	93.6	36.7	6.4	50.5
FR3	Loire-Atlantique	33.8	43.8	33.7	1.5	8.5
FR4	Moselle	54.5	89.3	66.6	0.7	22.0
FR5	Lyon & Grenoble	81.9	27.5	7.2	5.2	15.2
FR6	Bouches-du-Rhone	78.6	95.9	25.1	3.9	66.9
IT1	Rome	76.9	63.9	54.6	1.6	7.7
IT2	Bologna & Ferrara	81.6	82.4	68.5	3.8	10.1
IT3	Verona & Bergamo	76.9	31.7	9.4	7.1	15.2
IT4	Milano	139.7	79.5	47.0	9.5	23.1
IT5	Torino	66.6	39.5	32.6	0.0	6.9
SI1	Ljubljana	11.8	4.6	4.6	0.0	0.0
SI2	Celje & Trbovlje	6.8	30.0	29.1	0.2	0.7
Total		**2124.1**	**2554.9**	**1690.2**	**175.4**	**689.2**

Table 18. Total annual residential and service sector heat demand in buildings (HD) and total excess heat volumes (EH), specified by activity sectors: Thermal power (TP), Waste-to-Energy (WTE), and Industrial (Ind), for 18 strategic heat synergy regions in category New Development. Detail of study results from appended Paper VI

Label	**Name**	**HD [PJ/a]**	**EH [PJ/a]**	**TP [PJ/a]**	**WTE [PJ/a]**	**Ind [PJ/a]**
BE1	Brussels	54.7	16.3	13.2	3.1	0.0
BE2	Antwerp	39.8	90.5	15.2	3.0	72.2
BE3	Gent & Brugge	25.9	68.5	50.6	1.9	16.0
BE4	Charleroi	13.9	20.2	13.4	0.7	6.1
BE5	Liège	20.0	28.8	17.7	2.3	8.8
IE1	Dublin	46.2	33.0	29.5	1.2	2.3
IE2	Cork	16.4	12.9	10.8	0.0	2.1
LU1	Luxemburg	22.4	13.2	8.0	0.9	4.2
NL1	Rotterdam	75.0	286.0	171.4	14.6	99.9
NL2	Amsterdam	55.1	99.9	66.9	12.9	20.1
NL3	Arnhem	23.6	22.1	17.0	4.0	1.1
NL4	Maastricht	28.1	38.9	16.7	0.0	22.2
UK1	London & East Thames	149.5	150.7	121.4	11.8	17.5
UK2	Southampton & Oxford	68.9	118.7	62.8	4.9	51.0
UK3	Bristol & Cardiff	36.8	88.1	62.6	0.0	25.4
UK4	Liverpool & Chester	27.1	152.7	122.2	3.6	26.9
UK5	Grimsby & Kingston upon Hull	15.6	139.0	92.7	0.3	46.0
UK6	Edinburgh & Falkirk	22.9	125.5	93.9	0.7	30.9
Total		**741.7**	**1505.0**	**986.1**	**65.9**	**452.9**

Table 19. Total annual residential and service sector heat demand in buildings (HD) and total excess heat volumes (EH), specified by activity sectors: Thermal power (TP), Waste-to-Energy (WTE), and Industrial (Ind), for 23 strategic heat synergy regions in category Refurbishment. Detail of study results from appended Paper VI

Label	**Name**	**HD [PJ/a]**	**EH [PJ/a]**	**TP [PJ/a]**	**WTE [PJ/a]**	**Ind [PJ/a]**
BG1	Sofia & Pernik	13.5	10.7	10.2	0.0	0.5
BG2	Varna & Burgas	8.0	36.9	25.3	0.0	11.6
CZ1	Prague & Kladno	64.0	56.7	45.9	2.8	8.1
CZ2	Ustecky kraj	21.4	143.5	121.9	0.0	21.6
CZ3	Ostrava	31.6	69.4	49.2	0.0	20.2
CZ4	Brno	28.7	9.2	4.8	1.5	2.9
HU1	Budapest & Fejer	81.1	49.8	31.8	2.8	15.3
HU2	Miskolc	17.5	23.5	15.7	0.1	7.7
HU3	Baranya	8.9	5.2	3.9	0.0	1.3
PL1	Warsaw	38.2	34.1	33.8	0.3	0.0
PL2	Gdansk & Gdynia	16.2	22.0	11.1	0.0	11.0
PL3	Szczecin	15.5	38.7	35.6	0.0	3.1
PL4	Central	61.6	139.4	81.7	0.0	57.7
PL5	South Central	100.1	247.6	207.5	0.0	40.1
PL6	Cracow & Bielsko-Biala	58.8	44.1	35.3	0.0	8.8
RO1	Bucharest	25.9	15.0	15.0	0.0	0.0
RO2	Constanta	9.3	9.6	3.4	0.0	6.2
RO3	Galati & Bacau	18.3	25.5	6.6	0.0	18.8
RO4	Central	41.0	40.1	13.6	0.0	26.5
RO5	Craiova	9.5	29.9	29.4	0.0	0.5
SK1	Bratislava	13.5	20.5	8.5	0.8	11.2
SK2	Trencin & Prievidza	13.3	16.8	14.4	0.0	2.4
SK3	Kosicky kraj	17.6	38.2	10.9	0.0	27.4
Total		**713.5**	**1126.7**	**815.5**	**8.3**	**302.9**